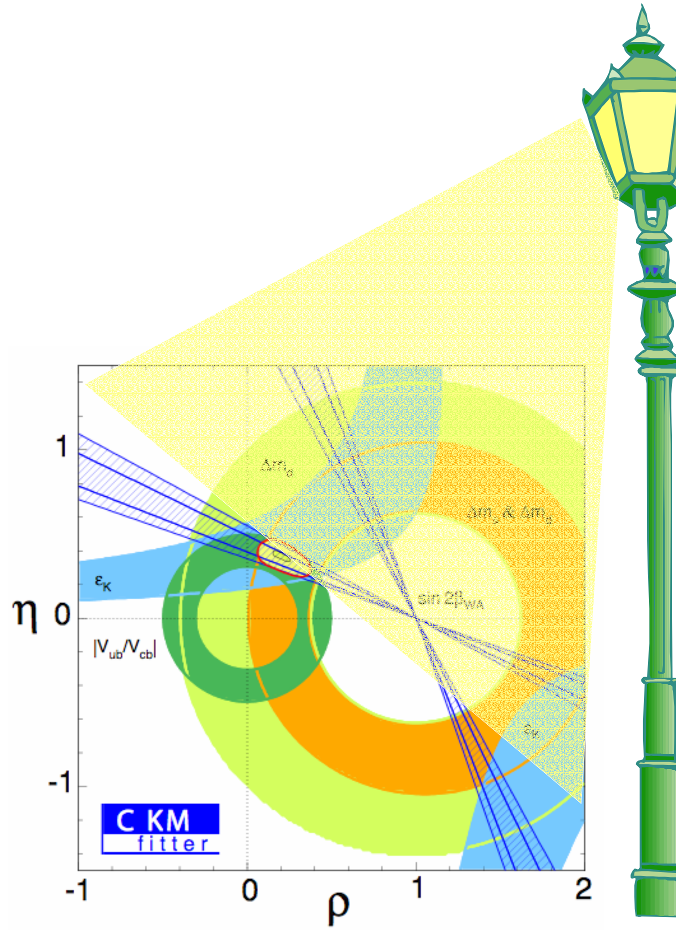
B-Factories and B-Physics

- Why study heavy flavors?
- Flavor Physics 101
  - Angles, triangles, mixing, CPV…
- What must be done?
  - Don't just look under the streetlight!
- The next generation of B-factory
- Conclusions

(*Thanks to Harry Cheung, **Sheldon Stone**, & Eric Vaandering for many slides & ideas*)



(figure credit: Harry Cheung)

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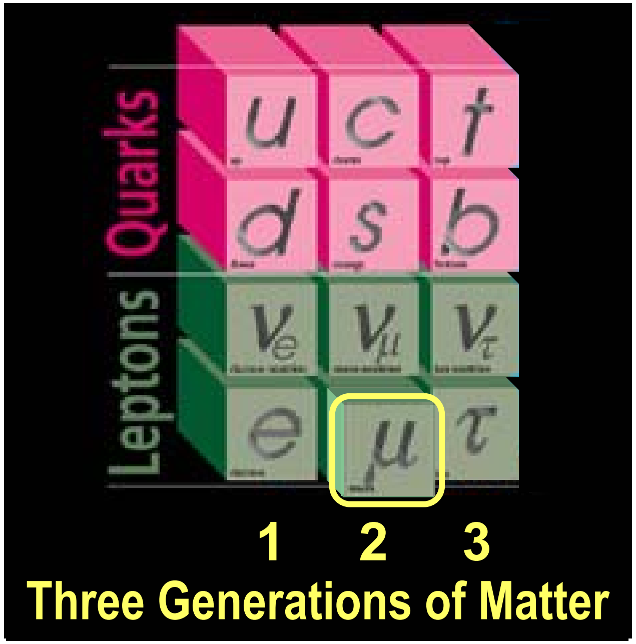
Paul Sheldon
Vanderbilt University

The Birth of Flavor

Discovery of the muon (late 1930's)
gave birth to the

→ generation (or flavor) puzzle ←

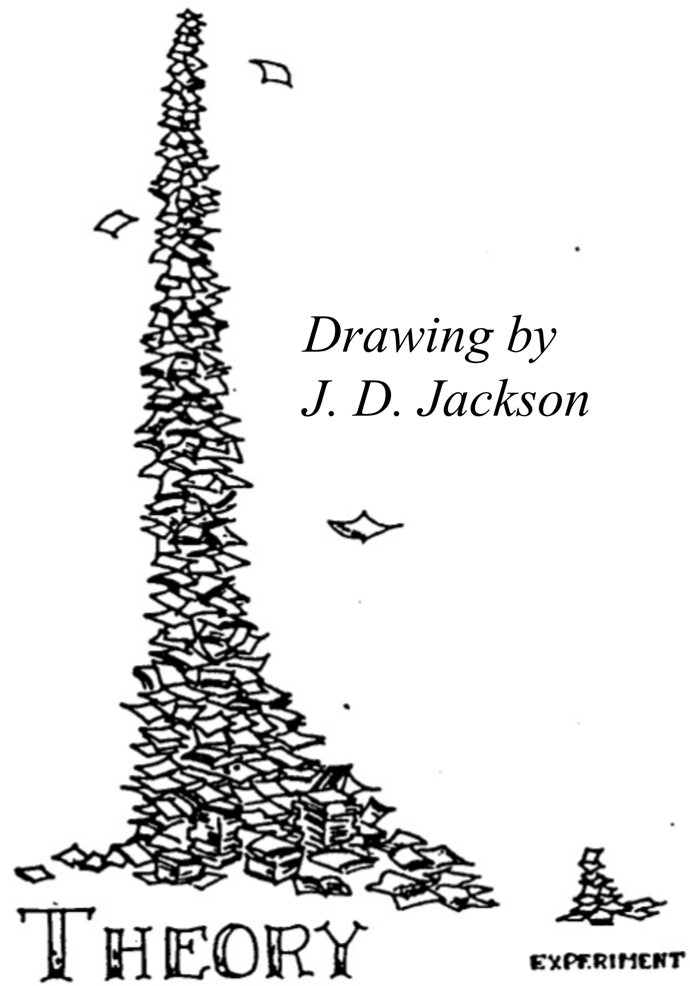
"Who ordered *that*?"
(I. I. Rabi)



Study of flavors has **transformed** our **understanding** of the **fundamental interactions** and **symmetries** of nature**...**

Transforming Physics

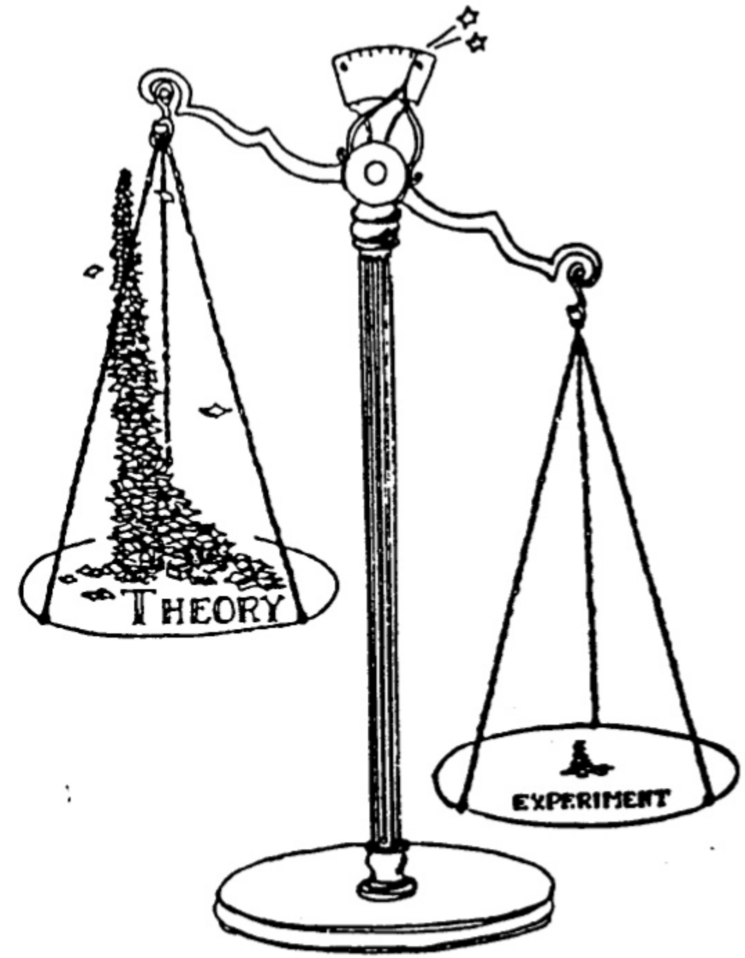
- Example: discovery of charm ("November revolution," 1974)
  - Fourth quark (charm) hypothesized earlier by Glashow, Iliopoulos, and Maiani to suppress Flavor Changing Neutral Currents



Drawing by J. D. Jackson

Transforming Physics

- Example: discovery of charm ("November revolution," 1974)
  - Fourth quark (charm) hypothesized earlier by Glashow, Iliopoulos, and Maiani to suppress Flavor Changing Neutral Currents
  - Discovery gave quark model and electroweak unification instant and widespread credibility
  - Was for many the defining event that lifted guage theory of fundamental interactions (Standard Model) to its current state of "supremacy."



...embellished by Roy Schwitters

Must be New Physics

- Abundant clues that there is new physics to be discovered
  - Standard Model (SM) is unable to explain baryon asymmetry of the universe and cannot currently explain dark matter or dark energy
  - New theories hypothesize extra dimensions in space or new symmetries (supersymmetry) to solve problems with quantum gravity and divergent couplings at the unification scale
- Flavor physics will be an equal partner to high p_t physics in the LHC era… **explore at the high statistics frontier** what can't be explored at the energy frontier.
- Will spend a lot of time talking about what the SM predicts… but keep in mind that there is almost certainly something new to be discovered: the point is to look for *deviations* from SM predictions!!!!

Flavor Physics 101

Lets spend some time "reviewing"…

- CKM 101
  - The Cabibbo Kobayashi Maskawa (CKM) matrix translates between the quark flavor eigenstates (d, s, b) and the weak equivalents.
  - Unitarity of the CKM has several consequences, including those ubiquitous angles and triangles…
- Mixing 101
  - Mixing
  - CPV and Mixing

CKM 101

- Quark flavors are not eigenstates of the Weak Hamiltonian:

$$\text{weak eigenstates}\quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \text{mass eigenstates}$$

- Transformation matrix **V** is unitary, imaginary elements OK

$$\begin{pmatrix} V_{11}e^{i\phi_{11}} & V_{12}e^{i\phi_{12}} & V_{13}e^{i\phi_{13}} \\ V_{21}e^{i\phi_{21}} & V_{22}e^{i\phi_{22}} & V_{23}e^{i\phi_{23}} \\ V_{31}e^{i\phi_{31}} & V_{32}e^{i\phi_{32}} & V_{33}e^{i\phi_{33}} \end{pmatrix}$$

18 parameters

unitarity

(As we will see…)

4 free parameters
(1 can be imaginary)

- Called CKM matrix after Cabibbo, Kobayashi, Maskawa

Quark Wavefunctions

- Absorb 5 complex phases into quark wavefunctions:

$$\begin{pmatrix} V_{11} & V_{12} & V_{13} \\ V_{21} & V_{22}e^{i\phi_1} & V_{23}e^{i\phi_2} \\ V_{31} & V_{32}e^{i\phi_3} & V_{33}e^{i\phi_4} \end{pmatrix}$$

e.g. $|d'\rangle \rightarrow e^{i\phi_{11}}|d'\rangle$ leaves
9 real parameters,
4 imaginary phases

- I will also use without proof that: $\mathbf{V}^{-1} = \tilde{\mathbf{V}}^*$

Unitary Constraints

- $\mathbf{V}^{-1} = \tilde{\mathbf{V}}^* \;\; \rightarrow \;\; \tilde{\mathbf{V}}^* \cdot \mathbf{V} = \overleftrightarrow{\mathbf{1}}$ gives 9 equations …

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

  - Three (on the diagonal) that don't constrain phases:

$$V_{ud}^* V_{ud} + V_{cd}^* V_{cd} + V_{td}^* V_{td} = 1 = \left|V_{ud}\right|^2 + \left|V_{cd}\right|^2 + \left|V_{td}\right|^2$$

  - Six (three independent) off diagonal that constrain both:

$$V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} = 0 \Rightarrow$$

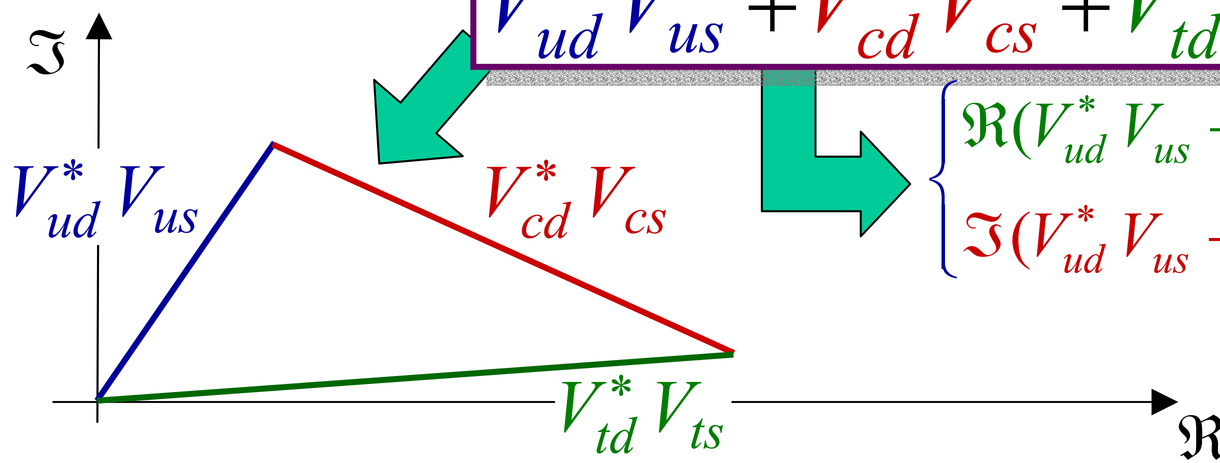
Unitary Triangles!

Four CKM Parameters

- 6 off diagonal equations (3 independent) from $\mathbf{V}\cdot\tilde{\mathbf{V}}^{*}=\overleftrightarrow{\mathbf{1}}$ give triangles in the complex plane:

$$\boxed{V_{ud}^{*}V_{us}+V_{cd}^{*}V_{cs}+V_{td}^{*}V_{ts}=0}$$

$$\begin{Bmatrix} \Re(V_{ud}^{*}V_{us}+V_{cd}^{*}V_{cs}+V_{td}^{*}V_{ts})=0 \\ \Im(V_{ud}^{*}V_{us}+V_{cd}^{*}V_{cs}+V_{td}^{*}V_{ts})=0 \end{Bmatrix}$$



- More on these triangles in a second, but for now…

Important!! *Imaginary phase* is allowed…

PARAMS:	real	imag
Started with:	**9**	**4**
Constraints:	**6**	**3**
Leaving:	**3**	**1**

Parameterize CKM!

Wolfenstein Param of CKM

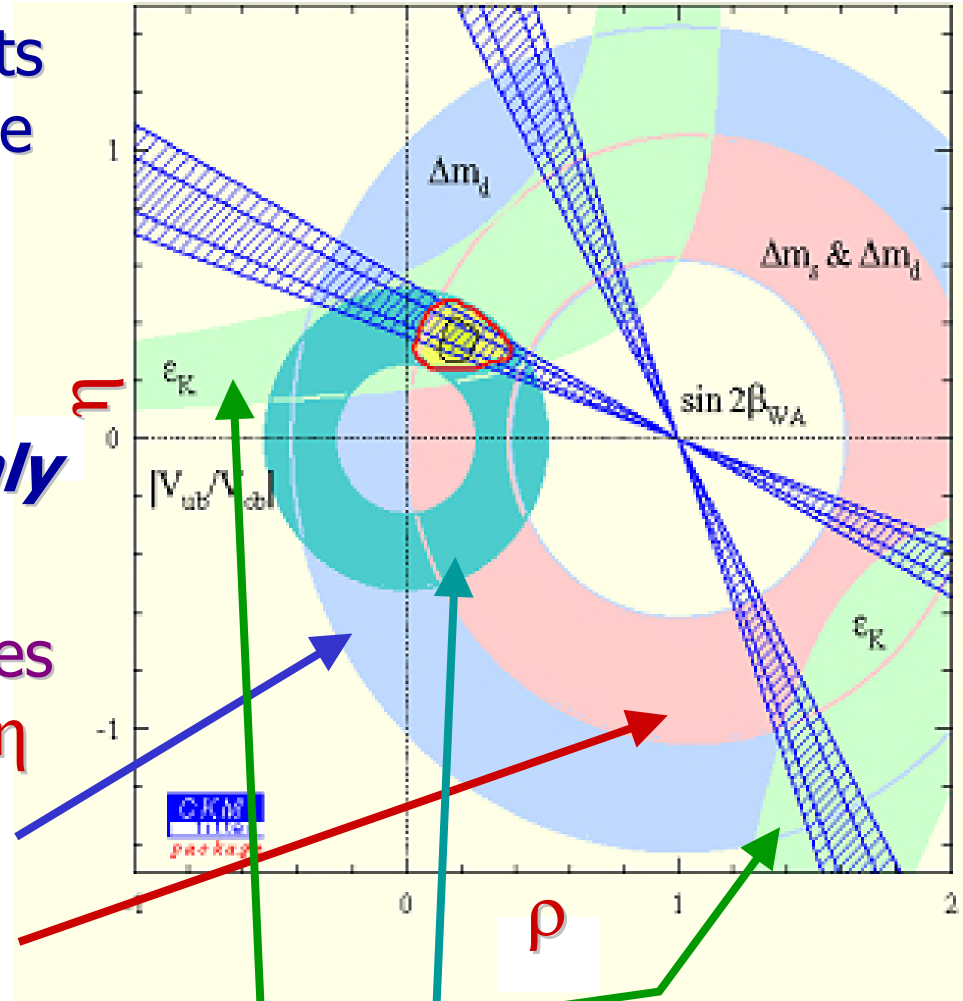
$$\mathbf{V} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3\left(\rho - i\eta(1-\frac{1}{2}\lambda^2)\right) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Four params: A, λ, ρ, η. These are fundamental constants in the standard model like G or α_{EM}
- Imaginary parts (η) allow for CP violation
- A ~ 0.8 and $V_{us} = \lambda = 0.22$, have constraints on ρ and η
- Other parameterizations possible, even one with four phases!

Constraints on ρ, η

The ρ–η plane

- As we will show, measmnts such as mixing give unique constraints in ρ, η plane.
- Recall $\eta \neq 0$ means CPV
- ***Constraints assume only SM physics*.**
- Big theoretical uncertainties (usually) in extracting ρ, η



B_d^0 mixing

B_s^0 mixing

CPV in K^0 mixing

Cabibbo suppressed B semileptonic decay

The Six CKM Triangles...

- Recall that the CKM...

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Must be unitary in the SM: $\mathbf{V} \cdot \tilde{\mathbf{V}}^* = \overleftrightarrow{\mathbf{1}}$ $\left(\mathbf{V}^{-1} = \tilde{\mathbf{V}}^*\right)$
- The off-diagonal products give six equations like:

$$(\text{columns } d, s) \Rightarrow V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0$$

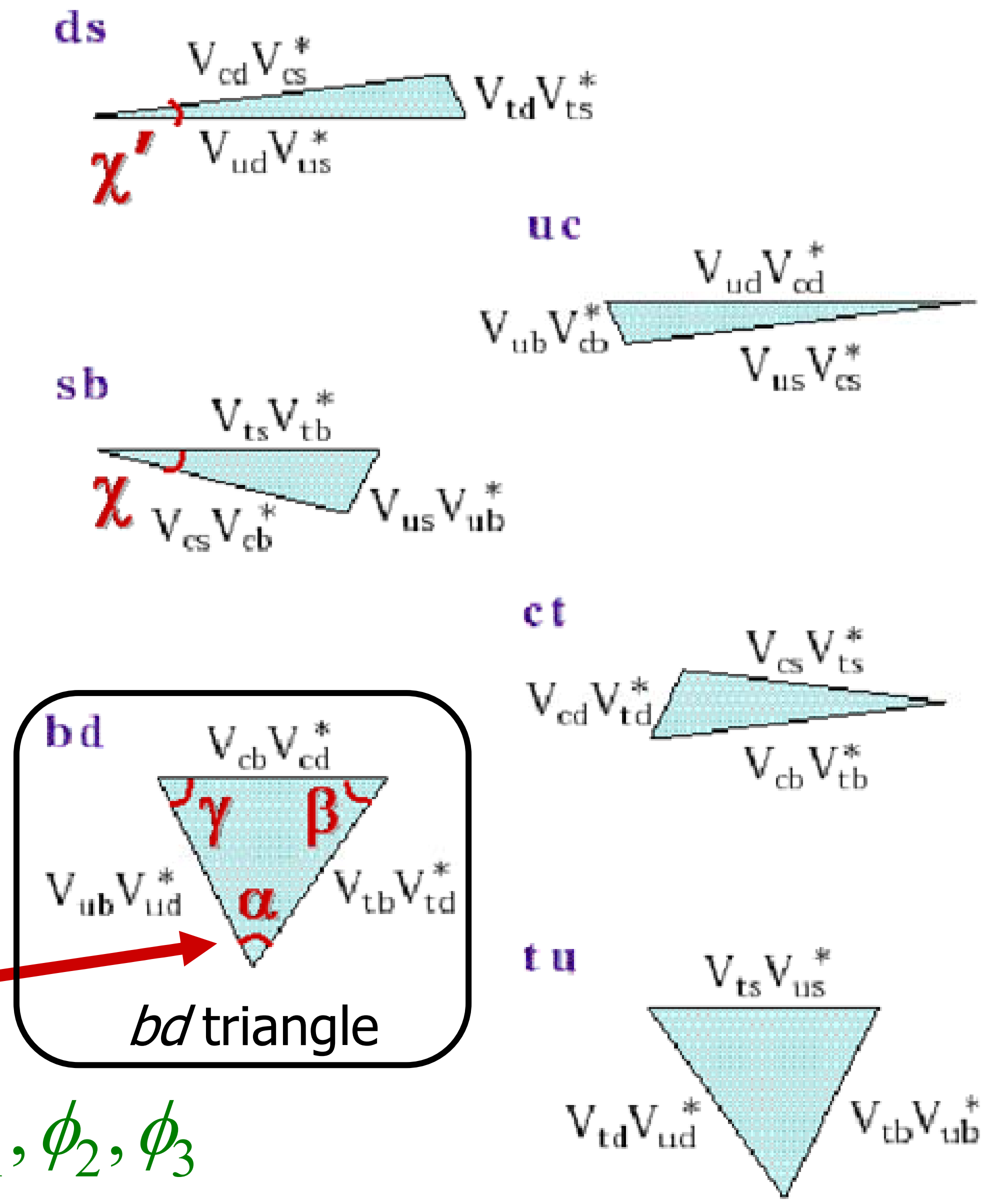
$$(\text{columns } s, b) \Rightarrow V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0$$

$$(\text{rows } u, c) \Rightarrow V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cd}^* = 0$$

Unitary Triangles!

...The Six CKM Triangles

- In the complex plane these equations can be represented as triangles…
- *Aleksan, Kayser, & London* alternative to Wolfenstien params: $\alpha, \beta, \chi, \chi'$
- People often refer to α, β, γ. **Note:** these aren't independent… $\alpha = \pi - (\beta + \gamma)$



- α, β, γ are also called: ϕ_1, ϕ_2, ϕ_3

The *bd* Triangle and ρ–η

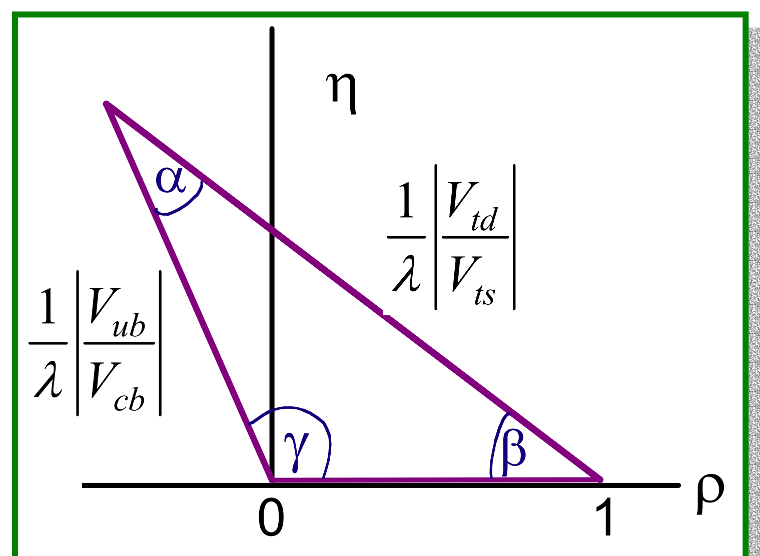
$$
\begin{array}{c} \\ u \\ c \\ t \end{array}
\begin{array}{c}
\begin{array}{ccc} \quad d \quad & \quad s \quad & \quad b \quad \end{array} \\
\begin{pmatrix}
1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3\left(\rho - i\eta(1-\frac{1}{2}\lambda^2)\right) \\
-\lambda & 1-\frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\
A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\end{array}
$$

$$V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0 \xrightarrow{\left|V_{ud}^*\right| \approx \left|V_{tb}\right| \approx 1} \frac{V_{ub}}{V_{cb}} + \frac{V_{td}^*}{V_{cb}} + V_{cd}^* = 0$$

Normalizing to V_{cd}^*, this gives a triangle with sides of length 1 and:

$$\left|\frac{V_{td}}{A\lambda^3}\right| = \sqrt{(\rho-1)^2+\eta^2} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{ts}}\right|$$

$$\left|\frac{V_{ub}}{A\lambda^3}\right| = \sqrt{\rho^2+\eta^2} = \frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$



“Angle” Parameterization

$$
\begin{array}{c}
 \\ u \\ c \\ t
\end{array}
\begin{array}{c}
\begin{array}{ccc} \quad d \quad & \quad s \quad & \quad b \quad \end{array} \\
\begin{pmatrix}
1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3\left(\rho-i\eta(1-\frac{1}{2}\lambda^2)\right) \\
-\lambda & 1-\frac{1}{2}\lambda^2-i\eta A^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\
A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\end{array}
$$

$$\beta = \arg\left(-\frac{V_{tb}V_{td}^*}{V_{cb}V_{cd}^*}\right) = \arg\left(1-\rho+i\eta\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}}\right) = \arg\left(\rho+i\eta\right)$$

$$\chi = \arg\left(-\frac{V_{cs}^*V_{cb}}{V_{ts}^*V_{tb}}\right) = \arg\left(1+i\eta\lambda^2\right)$$

$$\chi' = \arg\left(-\frac{V_{ud}^*V_{us}}{V_{cd}^*V_{cs}}\right) = \arg\left(1+i\eta A^2\lambda^4\right)$$

- χ is small (~ 2°, B_s mixing), χ' is even smaller (K^0 mixing)

Mixing 101

- Neutral B hadrons produced in interactions have definite quark content (flavor eigenstates): $\overline{B}^0 = b\overline{d}; \quad B^0 = \overline{b}d$
- These are not eigenstates of the Hamiltonian, so they evolve in time via the Schrödinger equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0 \\ \overline{B}^0 \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{12}^* & H_{11} \end{pmatrix}\begin{pmatrix} B^0 \\ \overline{B}^0 \end{pmatrix} \qquad H_{ij} = M_{ij} - i\Gamma_{ij}/2$$

- Diagonalizing, one gets the mass eigenstates:

$$B_L = pB^0 + q\overline{B}^0 \qquad B_H = pB^0 - q\overline{B}^0 \qquad \left\{ \begin{array}{l} M_{H,L} = M \pm \Re\left[H_{12}H_{12}^*\right]^{1/2} = M \pm \frac{1}{2}\Delta M \\ \Gamma_{H,L} = \Gamma \mp 2\Im\left[H_{12}H_{12}^*\right]^{1/2} = \Gamma \mp \Delta\Gamma; \ \Delta\Gamma \sim 0 \end{array} \right\}$$

$$B_H(t) = e^{-iM_H t - \frac{1}{2}\Gamma_H t} B_H(0); \quad B_L(t) = e^{-iM_L t - \frac{1}{2}\Gamma_L t} B_L(0)$$

CP Eigenstates

- If Hamiltonian doesn't conserve CP, then the mass eigenstates B_L and B_H are not necessarily CP eigenstates
- CP eigenstates are:

$$\left|B_1^0\right\rangle = \tfrac{1}{\sqrt{2}}\left(\left|B^0\right\rangle + \left|\overline{B}^0\right\rangle\right) = \tfrac{1}{\sqrt{2}}\left(\left|\overline{b}d\right\rangle + \left|b\overline{d}\right\rangle\right)$$

$$\left|B_2^0\right\rangle = \tfrac{1}{\sqrt{2}}\left(\left|B^0\right\rangle - \left|\overline{B}^0\right\rangle\right) = \tfrac{1}{\sqrt{2}}\left(\left|\overline{b}d\right\rangle - \left|b\overline{d}\right\rangle\right)$$

$$\mathrm{CP}\left|B_1^0\right\rangle = \tfrac{1}{\sqrt{2}}\left(\left|b\overline{d}\right\rangle + \left|\overline{b}d\right\rangle\right) = \tfrac{1}{\sqrt{2}}\left(\left|\overline{B}^0\right\rangle + \left|B^0\right\rangle\right) = \left|B_1^0\right\rangle$$

$$\mathrm{CP}\left|B_2^0\right\rangle = \tfrac{1}{\sqrt{2}}\left(\left|b\overline{d}\right\rangle - \left|\overline{b}d\right\rangle\right) = \tfrac{1}{\sqrt{2}}\left(\left|\overline{B}^0\right\rangle - \left|B^0\right\rangle\right) = -\left|B_2^0\right\rangle$$

- These are only equal to mass eigenstates if $p=q=1$, which is nearly true. $\left(\text{Recall: } B_L = pB^0 + q\overline{B}^0;\ \ B_H = pB^0 - q\overline{B}^0\right)$

Evolution of Flavor States

- Since $B_L = pB^0 + q\overline{B}^0; \quad B_H = pB^0 - q\overline{B}^0$
- The flavor eigenstates evolve in time as:

$$B_H(t) + B_L(t) = 2pB^0(t) = e^{-iM_H t - \frac{1}{2}\Gamma_H t} B_H(0) + e^{-iM_L t - \frac{1}{2}\Gamma_L t} B_L(0)$$

$$= e^{-iM_H t - \frac{1}{2}\Gamma_H t}\left(pB^0(0) + q\overline{B}^0(0)\right) + e^{-iM_L t - \frac{1}{2}\Gamma_L t}\left(pB^0(0) - q\overline{B}^0(0)\right)$$

$$= \left(e^{-iM_H t - \frac{1}{2}\Gamma_H t} + e^{-iM_L t - \frac{1}{2}\Gamma_L t}\right) pB^0(0) + \left(e^{-iM_H t - \frac{1}{2}\Gamma_H t} - e^{-iM_L t - \frac{1}{2}\Gamma_L t}\right) q\overline{B}^0(0)$$

$$= e^{-iMt - \frac{1}{2}\Gamma t}\left(e^{-i\frac{1}{2}\Delta M t} + e^{i\frac{1}{2}\Delta M t}\right) pB^0(0) + e^{-iMt - \frac{1}{2}\Gamma t}\left(e^{-i\frac{1}{2}\Delta M t} - e^{i\frac{1}{2}\Delta M t}\right) q\overline{B}^0(0)$$

- In this last step we used $\Delta\Gamma \sim 0$. This reduces to:

$$B^0(t) = e^{-iMt - \frac{1}{2}\Gamma t}\left(\cos\frac{\Delta M t}{2} B^0(0) \; + \; i\frac{q}{p}\sin\frac{\Delta M t}{2}\overline{B}^0(0)\right)$$

$$\overline{B}^0(t) = e^{-iMt - \frac{1}{2}\Gamma t}\left(i\frac{p}{q}\sin\frac{\Delta M t}{2} B^0(0) \; + \; \cos\frac{\Delta M t}{2}\overline{B}^0(0)\right)$$

B^0 "mixes" to a $\overline{B}^0$ with non-zero, time depen. probability

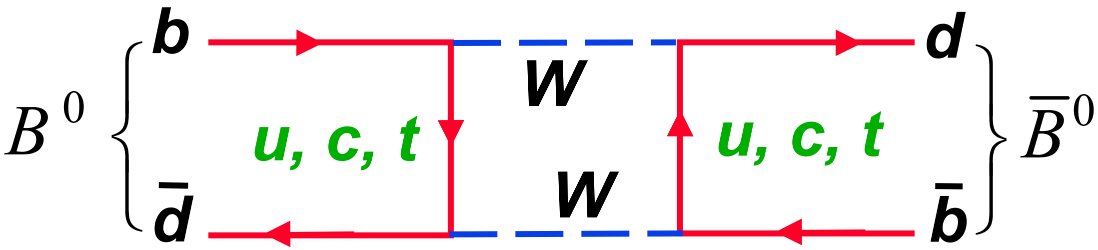
Efficiency and Tagging

- To observe mixing, must know what was originally produced: $\overline{B}^0$ or B^0: called "tagging" the initial state
- Tagging requirement effects the significance of result…
  - How efficient is your tag?
  - Dilution: mis-tag rate

$$D = \frac{\left(n_{\text{right}} - n_{\text{wrong}}\right)}{\left(n_{\text{right}} + n_{\text{wrong}}\right)}$$

- eD^2 is a "figure of merit" for tagging: gives effective efficiency after dilution of mis-tag.
  - 25-40% for e^+e^-, 10% at hadron colliders
- Typical tag methods:
  - Opposite side $K^\pm$
  - Opposite side lepton
  - Jet charge of opposite jet
  - Same side $\pi^\pm$ (B^0) or $K^\pm$ (B_s)

Neutral *B* Mixing



$+ \left\{ \right.$ similar diagram with "$W-u,c,t$" box rotated 90°

- Where: $\langle B^0 | H_{wk} | \bar{B}^0 \rangle \propto \left| \sum_{i=u,c,t} V_{bi}^* V_{di} F_i(m) \right|^2$
- Note that the sum would be a "unitary triangle" if not for the $F_i(m)$… $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$
- *i.e.* no mixing if $F_i(m)$ all equal, or if quark masses all equal.
- GIM mechanism! In charm sector, $F_i(m)$ are all small… mixing is extremely small (unless long range contribs).
- In beauty sector, top quark mass dominates, mixing big! (as we will see).

B_d Mixing

- Showed earlier: $B^0(t) = e^{-iMt - \frac{1}{2}\Gamma t}\left(\cos\frac{\Delta M t}{2} B^0(0) + i\frac{q}{p}\sin\frac{\Delta M t}{2}\bar{B}^0(0)\right)$
- Mixing probability: $\left\langle \bar{B}^0(0) \middle| B^0(t) \right\rangle = e^{-iMt - \frac{1}{2}\Gamma t}\left(i\frac{q}{p}\sin\frac{\Delta M t}{2}\right)$

$$\left.\begin{aligned} r_{\text{mix}}(t) &= \left|\left\langle \bar{B}^0(0) \middle| B^0(t) \right\rangle\right|^2 = \left|\frac{q}{p}\right|^2 e^{-\Gamma t}\sin^2\frac{\Delta M t}{2} \\ \bar{r}_{\text{mix}}(t) &= \left|\left\langle B^0(0) \middle| \bar{B}^0(t) \right\rangle\right|^2 = \left|\frac{p}{q}\right|^2 e^{-\Gamma t}\sin^2\frac{\Delta M t}{2} \end{aligned}\right\}$$

If |q/p|≠1, "indirect" CPV

- Integrating over time, no CPV:

$$\frac{r_{\text{mix}}}{r_{\text{no-mix}}} = \frac{x^2}{2+x^2}; \quad x = \frac{\Delta M}{\Gamma} \cong \frac{G_F^2}{6\pi^2} B_B\, f_B^2\, m_B\, \tau_B \left|V_{tb}^* V_{td}\right|^2 m_t^2\, F\left(\frac{m_t^2}{m_W^2}\right)\eta_{QCD}$$

- $B_B\, f_B^2$ is related to probability of *d* and $\bar{b}$ quarks forming a hadron, F is a known function ($\sim m_t^2$), and η_{QCD} is a QCD correction (~0.8).

B_d , B_s Mixing & ρ, η

$$B_d^0: \quad \frac{r_{\text{mix}}}{r_{\text{no-mix}}} = \frac{x^2}{2+x^2}; \quad x = \frac{\Delta M}{\Gamma} = \frac{G_F^2}{6\pi^2} B_B \, f_B^2 \, m_B \, \tau_B \left|V_{tb}^* V_{td}\right|^2 m_t^2 \, F\left(\frac{m_t^2}{m_W^2}\right) \eta_{QCD}$$

- Since $\left|V_{tb}^* V_{td}\right|^2 \propto \left|1-\rho-i\eta\right|^2 = (1-\rho)^2 + \eta^2$, mixing measurements give a circle centered at (1,0) in the ρ–η plane

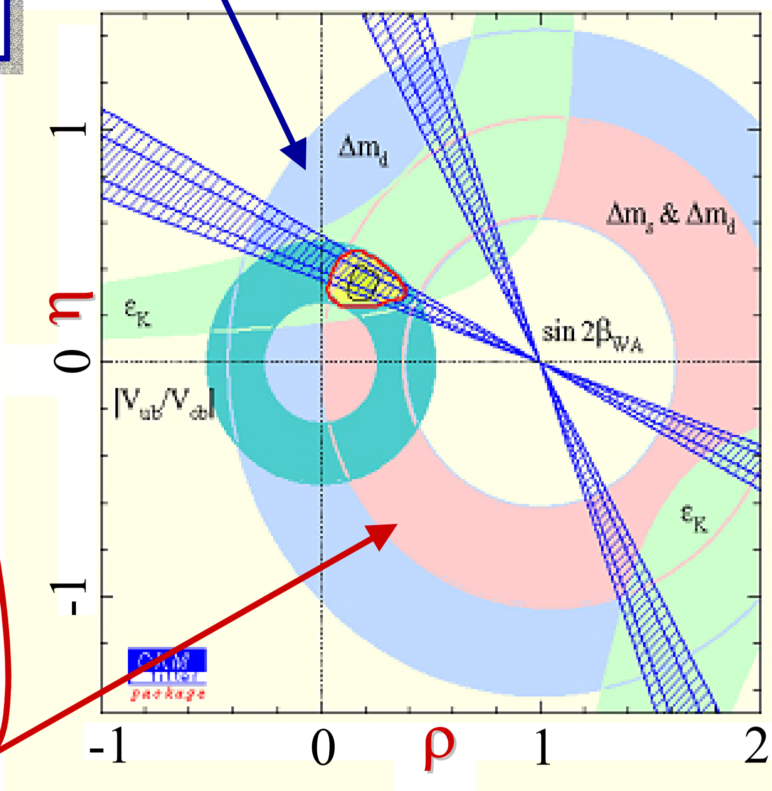
$$\Delta m_d = 0.502 \pm -.006 \text{ ps}^{-1} \text{ (World Avg)}$$

- Making a similar calculation for B_s:

$$\frac{\Delta M_s}{\Delta M_d} = \frac{B_s}{B} \frac{f_{B_s}^2}{f_B^2} \frac{m_{B_s}}{m_B} \left|\frac{V_{ts}}{V_{td}}\right|^2$$

$$\left|\frac{V_{td}}{V_{ts}}\right|^2 = \lambda^2\left[(1-\rho)^2 + \eta^2\right]$$

$$\Delta m_s < 14.4 \text{ ps}^{-1} \text{ @ 95\% CL}$$



- Constraint from this ratio has fewer theoretical uncertainties: cancel in the first two factors…

CPV in Mixing

- Biggest effects for case of interference of mixing & decay
- Choose a decay mode in which final state is accessible from both B^0 and $\overline{B}^0$, such as $J/\psi\, K_s^0$ or $\pi^+\pi^-$
- Even better if final state is a CP eigenstate (both above are)
- $B^0\,(\overline{B}^0)$ can then decay to this final state two ways

$$
\begin{tikzcd}
B^0 \arrow[rr, "\text{decay}"] \arrow[dr, "\text{mixing}"'] & & f_{CP} \\
& \overline{B}^0 \arrow[ur, "\text{decay}"'] &
\end{tikzcd}
$$

$$A_{\text{tot}} = A(B^0 \to f_{CP}) + A(B^0 \to \overline{B}^0 \to f_{CP})$$

Types of CPV in Mixing

$$\begin{tikzcd} B^0 \arrow[rr, "\text{decay}"] \arrow[dr, "\text{mixing}"'] & & f_{CP} \\ & \overline{B}^0 \arrow[ur, "\text{decay}"'] & \end{tikzcd}$$

$$A_{\text{tot}} = A(B^0 \to f_{CP}) + A(B^0 \to \overline{B}^0 \to f_{CP})$$

- Defining $A = \langle f_{CP} | \mathrm{H} | B^0 \rangle; \quad \overline{A} = \langle f_{CP} | \mathrm{H} | \overline{B}^0 \rangle$, CPV can occur if

[1] $\left|\overline{A}/A\right| \neq 1$ → **direct CPV** in this particular decay

In SM, due to interference of CKM phase and strong decay phases

[2] |q/p| ≠ 1 → **indirect CPV** due to mixing (like K^0 system)

[3] $\lambda = \dfrac{q}{p} \bullet \dfrac{\overline{A}}{A} \neq 1$ … Note: **NOT** Wolfenstein λ !!!

CPV due to **decay/mixing interference**

CPV can occur if |λ|=1 but λ imaginary

"Interference CPV"

- Defining: $A = \langle f_{CP} | \mathrm{H} | B^0 \rangle; \quad \bar{A} = \langle f_{CP} | \mathrm{H} | \bar{B}^0 \rangle; \quad \lambda = \frac{q}{p} \cdot \frac{\bar{A}}{A}$
- And starting with:

$$B^0(t) = e^{-iMt - \frac{1}{2}\Gamma t} \left(\cos\frac{\Delta M t}{2} B^0(0) \; + \; i\frac{q}{p}\sin\frac{\Delta M t}{2} \bar{B}^0(0) \right)$$

- One can show:

$$\Gamma(B^0(t) \to f_{CP}) = |A|^2 e^{-\Gamma t}\left[\cos^2\frac{\Delta M t}{2} + |\lambda|^2 \sin^2\frac{\Delta M t}{2} - \Im(\lambda)\sin\Delta M t\right]$$

$$\Gamma(\bar{B}^0(t) \to f_{CP}) = |A|^2 \left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left[|\lambda|^2\cos^2\frac{\Delta M t}{2} + \sin^2\frac{\Delta M t}{2} + \Im(\lambda)\sin\Delta M t\right]$$

- So the CP asymmetry (for |q/p|=1) is:

$$a_{CP} = \frac{\Gamma(B^0(t) \to f_{CP}) - \Gamma(\bar{B}^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\bar{B}^0(t) \to f_{CP})}$$

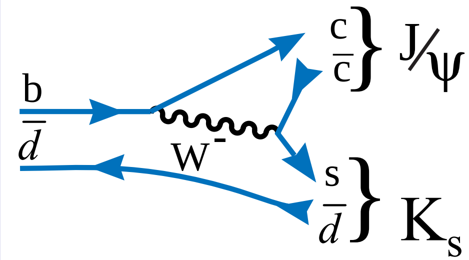
If $|\lambda|=1$

$$= \frac{(1-|\lambda|^2)\cos\Delta M t - 2\Im(\lambda)\sin\Delta M t}{1+|\lambda|^2} \quad = \quad -\Im(\lambda)\sin\Delta M t$$

CPV in $J/\psi\ K_s$

- So we need to evaluate $\Im(\lambda)$; $\lambda = \frac{q}{p} \bullet \frac{\bar{A}}{A}$

$B_d^0 \to J/\psi\ K_s$



- q/p comes from mixing:

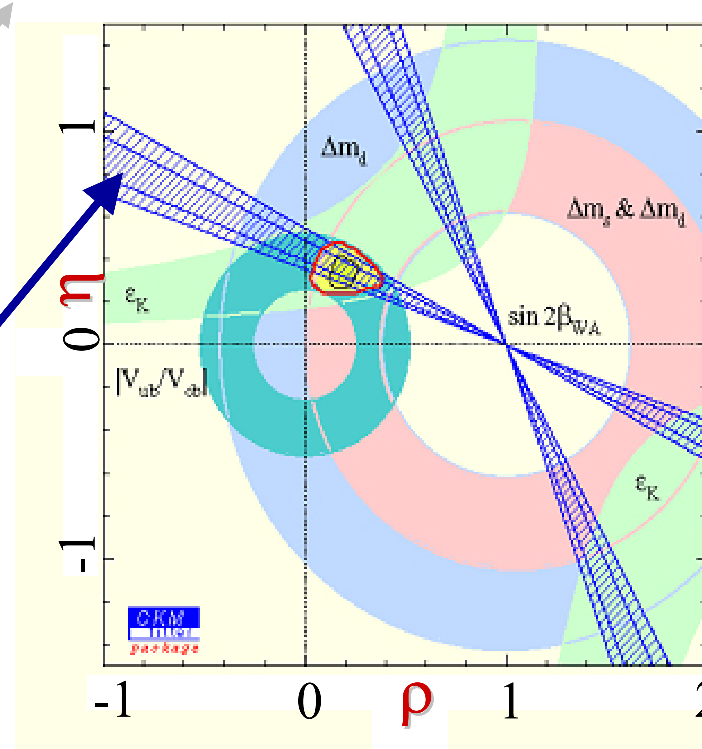
$$\frac{q}{p} = \frac{\left(V_{tb}^* V_{td}\right)^2}{\left|V_{tb}^* V_{td}\right|^2} = \frac{(1-\rho-i\eta)^2}{(1-\rho+i\eta)(1-\rho-i\eta)} = e^{-2i\beta}$$

- For the final state $J/\psi\ K_s^0$:

$$\frac{\bar{A}}{A} = \frac{\left(V_{cs}^* V_{cb}\right)^2}{\left|V_{cs}^* V_{cb}\right|^2} = 1$$

$$\Rightarrow\ \Im(\lambda) = -\sin(2\beta)$$

$$\boxed{\Rightarrow a_{CP} = \sin(2\beta)\sin(\Delta M t)}$$



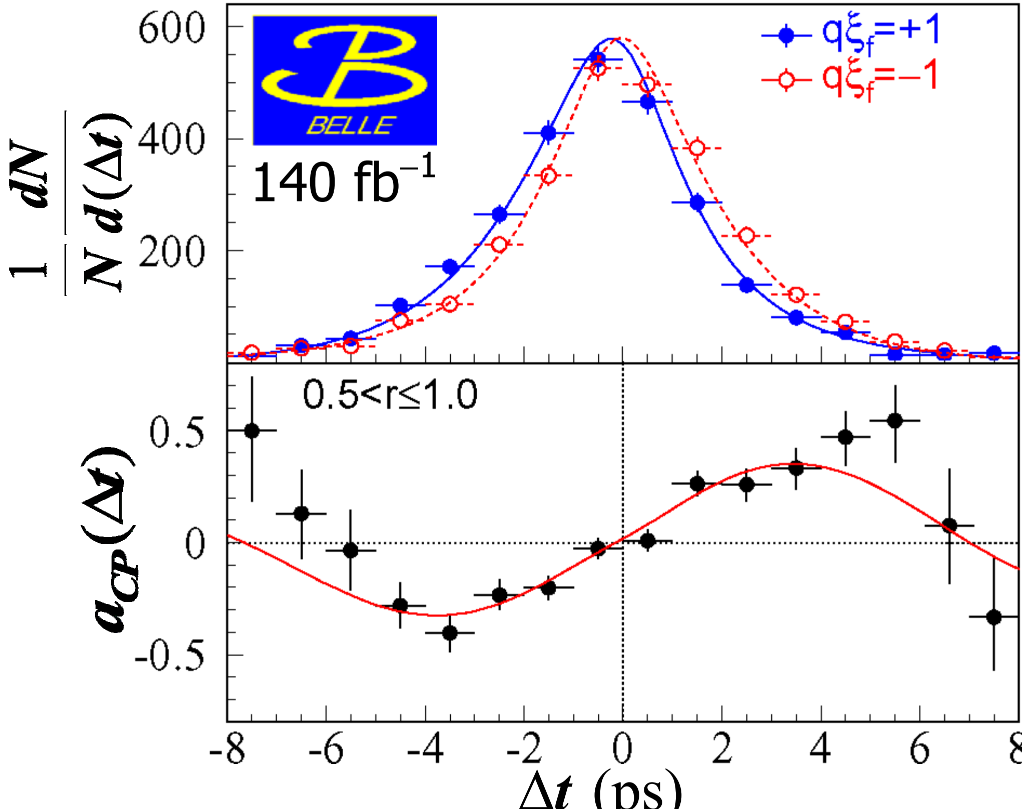
Status of sin(2β)

$$\sin 2\beta = 0.741 \pm 0.067 \pm 0.034 \quad \text{BaBar}$$

$$\sin 2\beta = 0.733 \pm 0.057 \pm 0.028 \quad \text{Belle}$$

$$\sin 2\beta = 0.736 \pm 0.049 \quad \text{Average}$$

No theoretical uncertainties at this level of error



$\bar{B}^0 \to f_{CP}$

$B^0 \to f_{CP}$

$$f_{CP} = J/\psi\, K_s,\ \psi' K_s, \ldots$$

$$a_{CP}(\Delta t) = \frac{N_{\bar{B}} - N_B}{N_{\bar{B}} + N_B} = \sin(2\beta)\sin(\Delta M \Delta t)$$

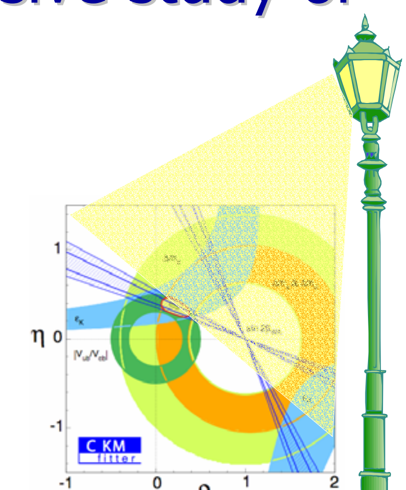
The Current Generation

- Current generation of B factories (BaBar, Belle) have established CPV in B decays and along with hadron collider experiments (CDF and D0) are producing a tremendous amount of excellent flavor physics and tantilizing results (more later). [Note: I have heard members of CDF refer to their experiment as "Charm Detector at Fermilab"]

- However, these "first generation" experiments cannot do what has to be done…

What Must Be Done

- There must be new physics, beyond SM
- Non-SM contributions will lead to disagreements where agreement was expected…
  - CKM Unitarity is not a given (4 generations)
  - New physics can change the relation between physics processes and parameters (will give an example for CPV in $B^0 \rightarrow \varphi K_s$ and sin2β).
- To discover new physics (or help interpret new physics discovered elsewhere) we need a comprehensive study of flavor physics
  - Need to measure α, β, γ, χ in many modes/decays
  - Look at rare b decays and mixing
  - Look at CP-violation and rare decays in charm
- Look beyond the streetlight!

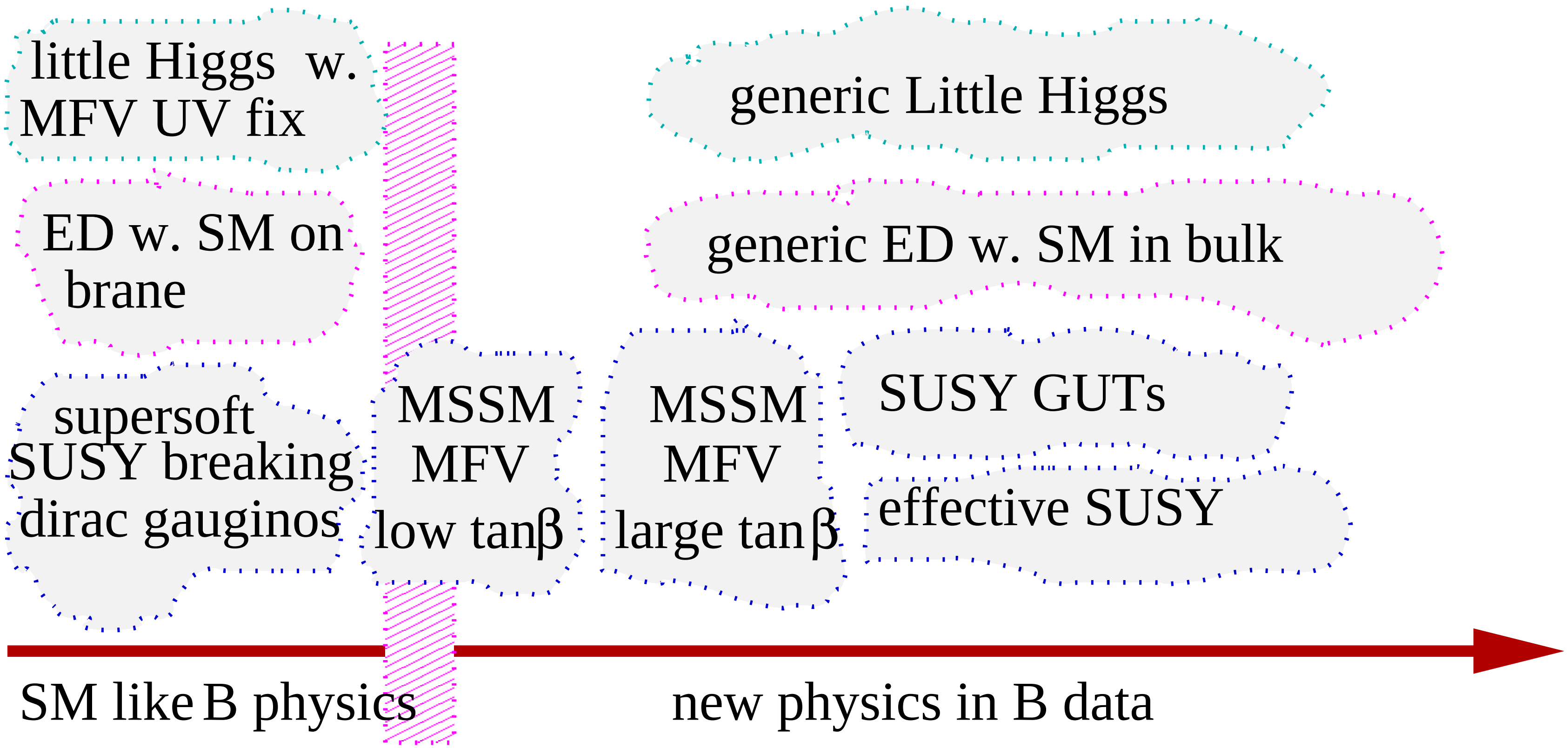


New Physics

- Masiero & Vives (hep-ph/0104027):
  "*the relevance of SUSY searches in rare processes is not confined to the usually quoted possibility that indirect searches can arrive 'first' in signaling the presence of SUSY. Even after the possible direct observation of SUSY particles, the importance of FCNC & CPV in testing SUSY remains of utmost relevance. They are & will be complementary to the Tevatron & LHC establishing low energy supersymmetry as the response to the electroweak breaking puzzle.*"

- **Replace "SUSY" with "New Physics" !!!**

Possible Size of New Physics Effects



- From Hiller hep-ph/0207121

Example: Supersymmetry

- Supersymmetry: In general 80 constants & 43 phases
- MSSM: 2 phases (Nir, hep-ph/9911321)
- New Physics in B^0 mixing: θ_D, B^o decay: θ_A, D^o mixing: $\varphi_{K\pi}$
- Predictions of $\theta_{D,}$ θ_A ,$\varphi_{K\pi}$ are of order 0.1—1.0

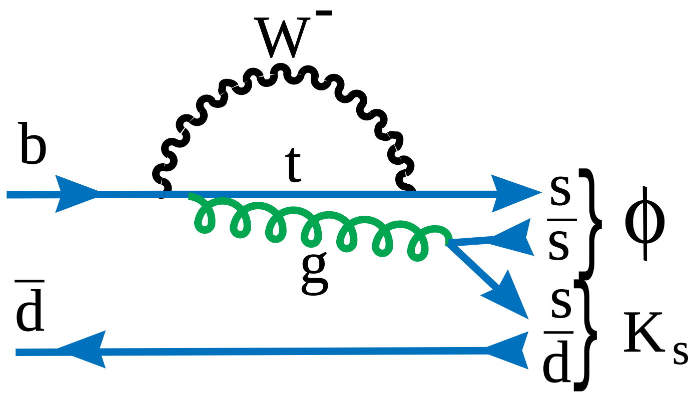
Process	Quantity	SM	New Physics
$B^0 \rightarrow J/\psi K_s$	CP asym	$\sin(2\beta)$	$\sin 2(\beta+\theta_D)$
$B^0 \rightarrow \varphi K_s$	CP asym	$\sin(2\beta)$	$\sin 2(\beta+\theta_D+\theta_A)$
$D^0 \rightarrow K^- \pi^+$	CP asym	0	$\sim\sin(\varphi_{K\pi})$

NP

NP

CP Asymmetry in $B^0 \rightarrow \phi K_s$

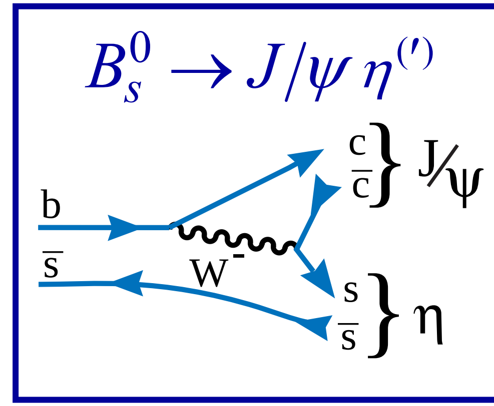
- Non-SM contributions would interfere with suppressed SM loop diagram



- Recall New Physics could produce a difference between sin(2β) measured here and in $B^0 \rightarrow J/\psi\ K_s$
- Belle: $\sin 2\beta_{eff}\ (B \rightarrow \varphi K_S) = -0.96 \pm 0.50^{+0.09}_{-0.11}$ ← 3.5σ off WA!!
- BaBar: $\sin 2\beta_{eff}\ (B \rightarrow \varphi K_S) = +0.45 \pm 0.43 \pm 0.07$
- There is a 2.1σ discrepancy between the exps.
- Average = –0.15±0.33 (Still 2.7σ from the SM)

[Current WA: sin(2β)=0.731±0.056]

Example 2: Measuring χ



- Use CP final states to measure χ, such as $B_s^0 \to J/\psi\,\eta^{(\prime)}$
- Mixing induced CPV asymmetry in such decays should be proportional to sin2χ
- The critical check is:

$$\sin\chi = \lambda^2 \frac{\sin\beta\sin\gamma}{\sin(\beta+\gamma)}$$

- Very sensitive since $\lambda = 0.2205 \pm 0.0018$
- Since $\chi \sim 2^o$, need lots of data
- Test suggested by Silva & Wolfenstein (hep-ph/9610208) and Aleksan, Kayser & London (hep-ph/9403341).

Requirements

- Large samples of tagged B^+, B^0, Bs decays, unbiased *b* and *c* decays
- Efficient Trigger, well understood acceptance and reconstruction
- Excellent vertex and momentum resolutions
- Excellent particle ID and γ, $\pi 0$ reconstruction

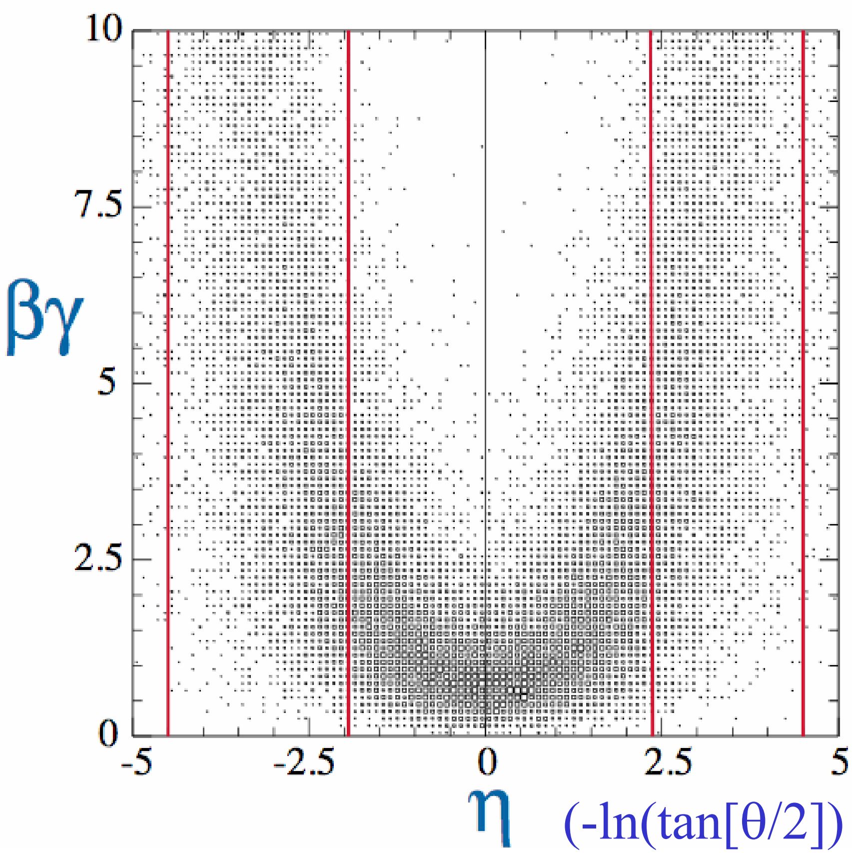
Physics Quantity	Decay Mode	Vertex Trig	K/π Sep	γ Det	Decay Time σ
$\sin(2\alpha)$	$B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$	✓	✓	✓	
$\cos(2\alpha)$	$B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$	✓	✓	✓	
$\sin(\gamma)$	$B_s \to D_s K^-$	✓	✓		✓
$\sin(\gamma)$	$B^0 \to D^0 K^-$	✓	✓		
$\sin(2\chi)$	$B_s \to J/\psi\eta$, $J/\psi\eta'$		✓	✓	✓
$\sin(2\beta)$	$B^0 \to J/\psi K_s$				
$\cos(2\beta)$	$B^0 \to J/\psi K^0$, $K^0 \to \pi l \nu$		✓		
x_s	$B_s \to D_s \pi^-$	✓	✓		✓
$\Delta\Gamma$ for B_s	$B_s \to J/\psi\eta^{(\prime)}$, K^+K^-, $D_s\pi$	✓	✓	✓	✓

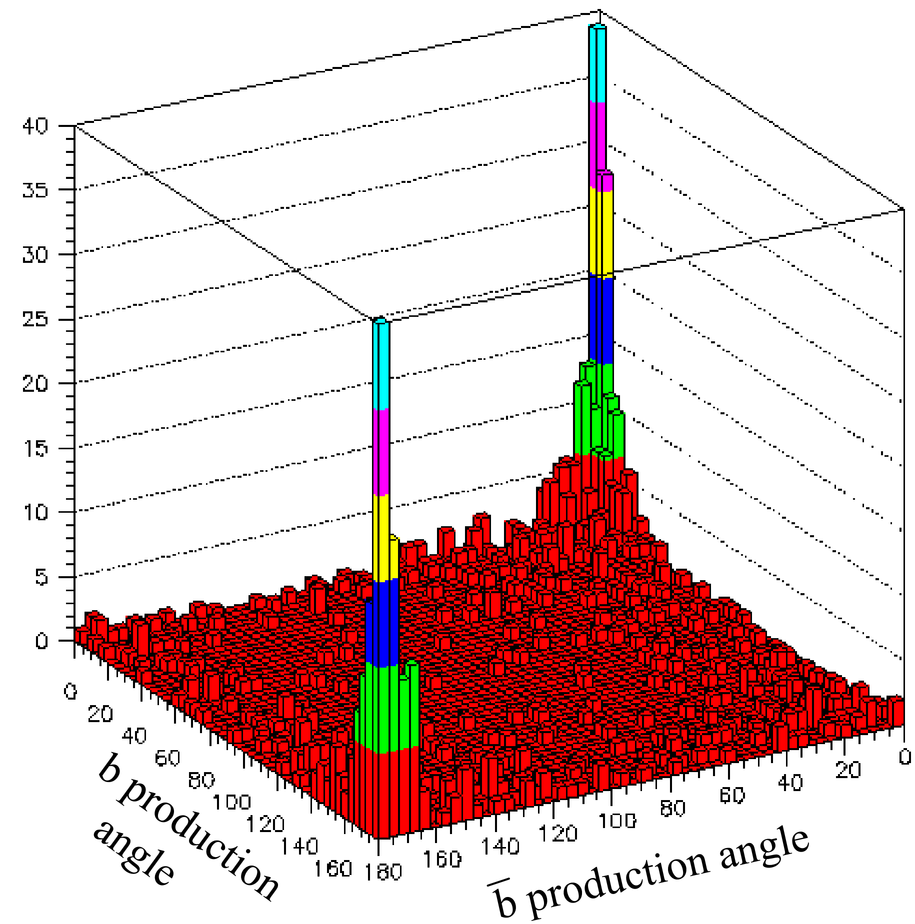
The Next Generation

- The next (2nd) generation of B-factories will be at hadron machines: BTeV and LHC-b
  - both will run in the LHC era.
- Why at hadron machines?
  - ~**10^{11}** b hadrons produced per year (10^7 secs) at 10^{32} $cm^{-2}s^{-1}$
  - **e^+e^-** at $\Upsilon(4s)$: ~**10^8** b produced per year (10^7 secs) at 10^{34} $cm^{-2}s^{-1}$
  - Get all varieties of b hadrons produced: B_s, baryons, etc.
  - Charm rates are 10x larger than b rates…
- Hadron environment is challenging…
  - CDF and D0 are showing the way
  - Technology improvements: BTeV will compute on every event!
  - Look in the forward direction…

Why Look Forward?

- Decay Length separation
- Reduced significance of MCS
- Excellent $\bar{B}B$ acceptance
- Better away side tagging

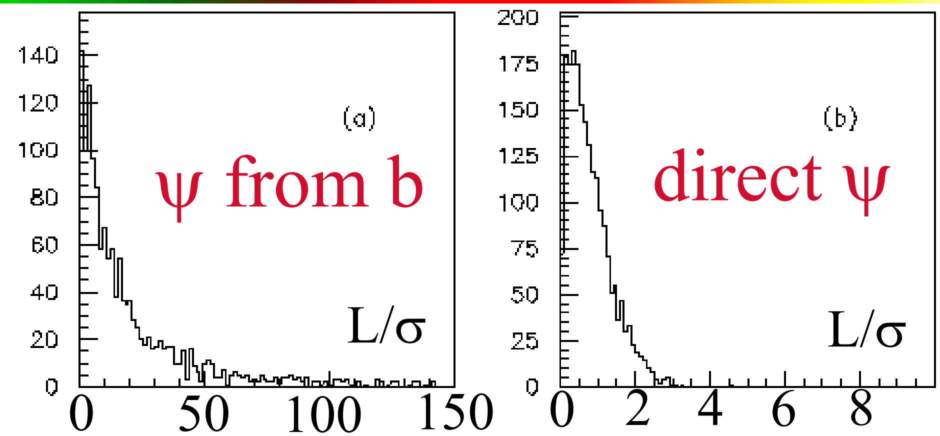




BTeV: $1.9 < |\eta| < 4.5$

Decay Time Resolution

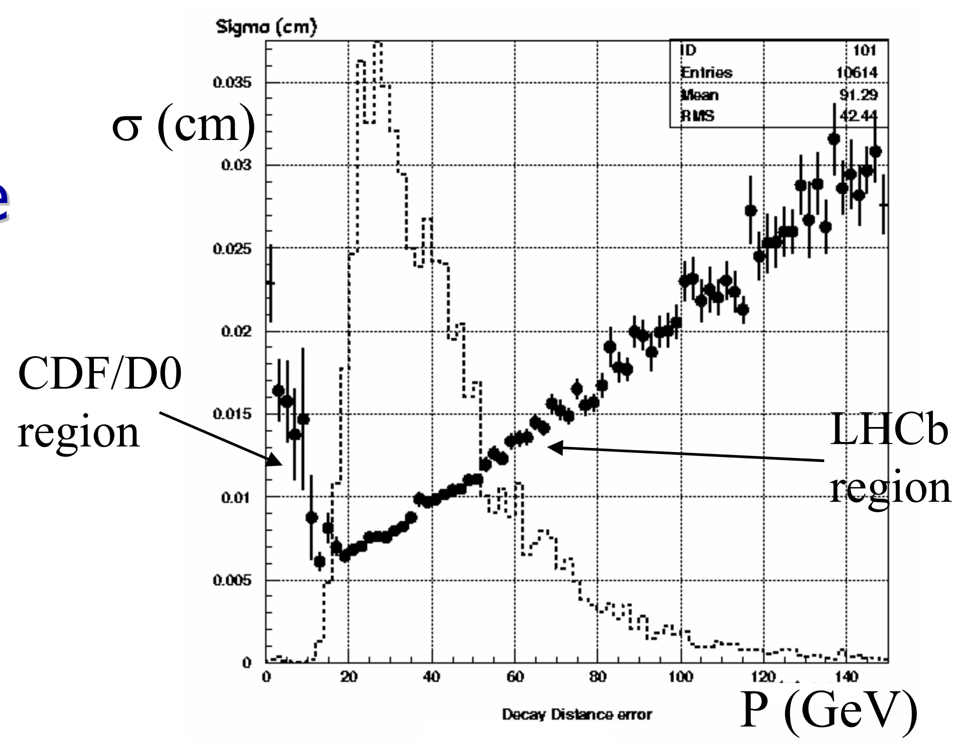
- Excellent decay time resolution
  - Reduces background
  - Allows detached vertex trigger



- The average decay distance and the uncertainty in the average decay distance are functions of B momentum:

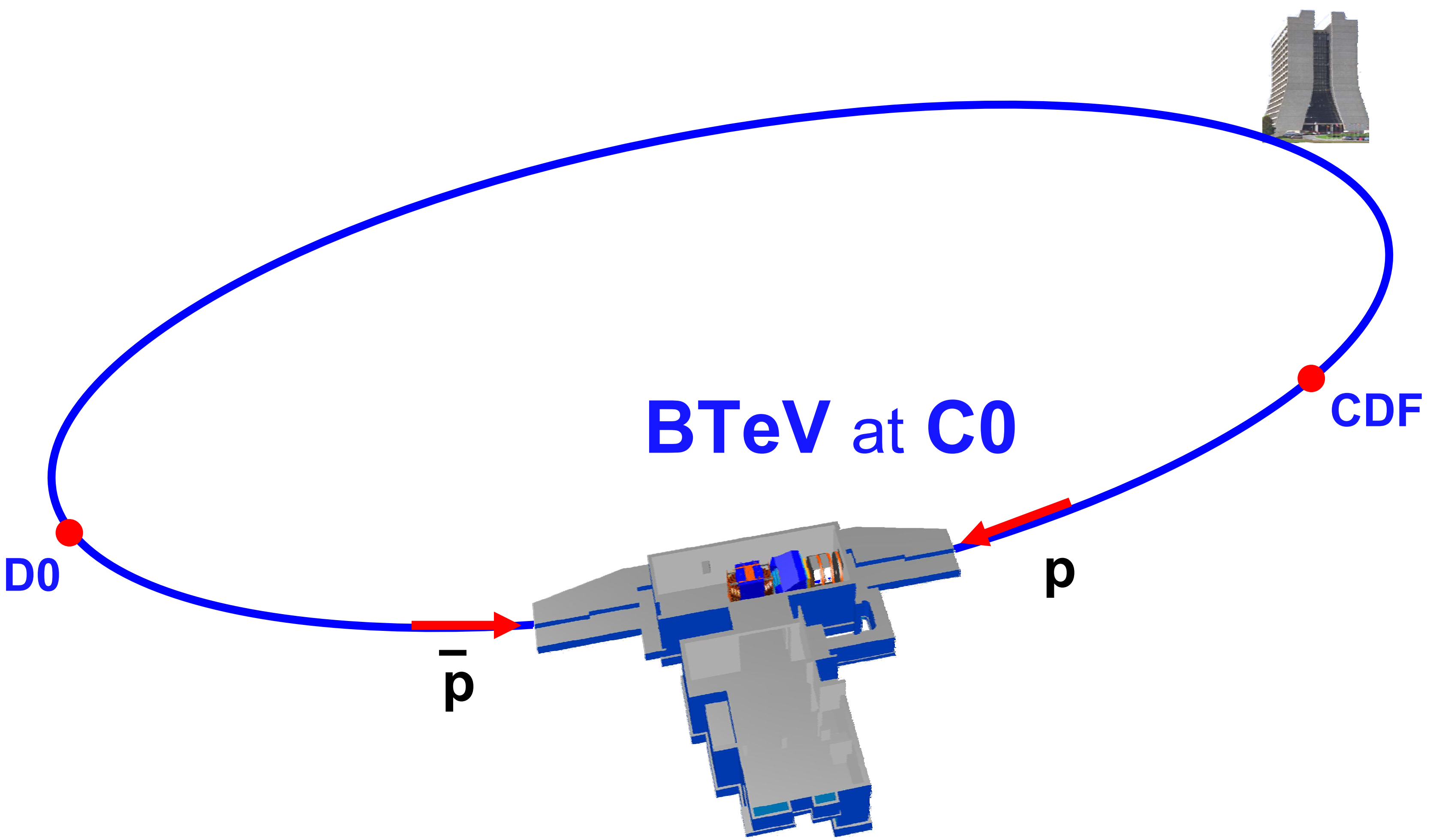
  $\langle L \rangle = \gamma\beta c\tau_B$

  $= 480\ \mu m \times p_B/m_B$



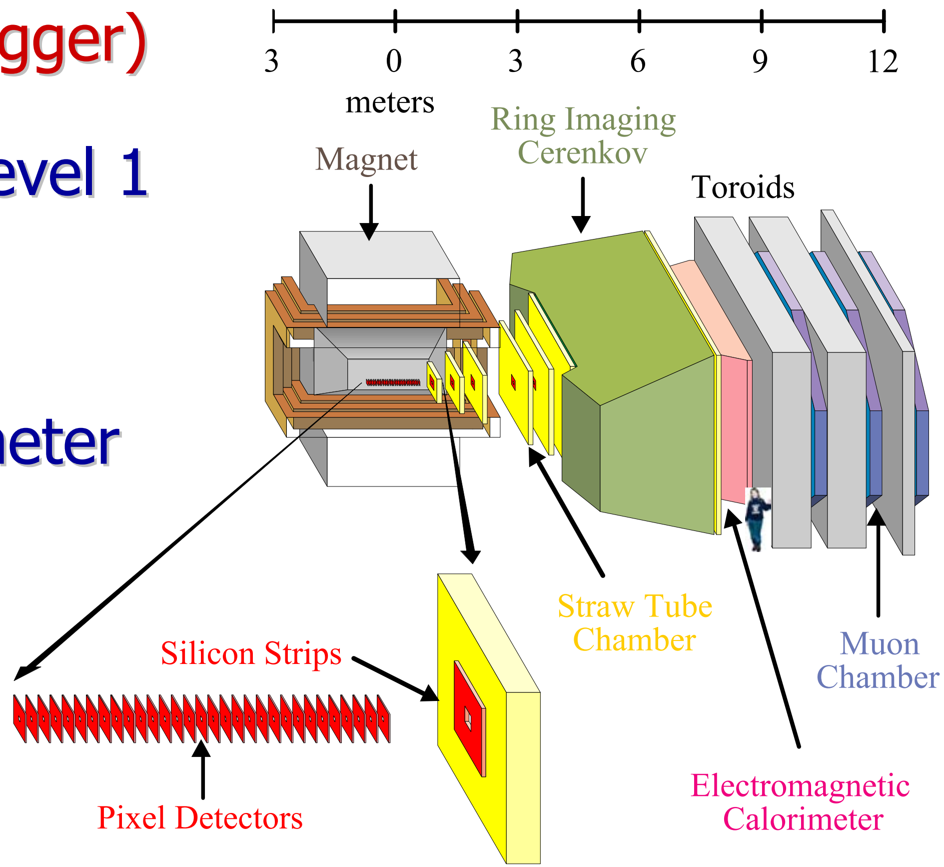
- Constant proper time resolution

BTeV at the FNAL Tevatron



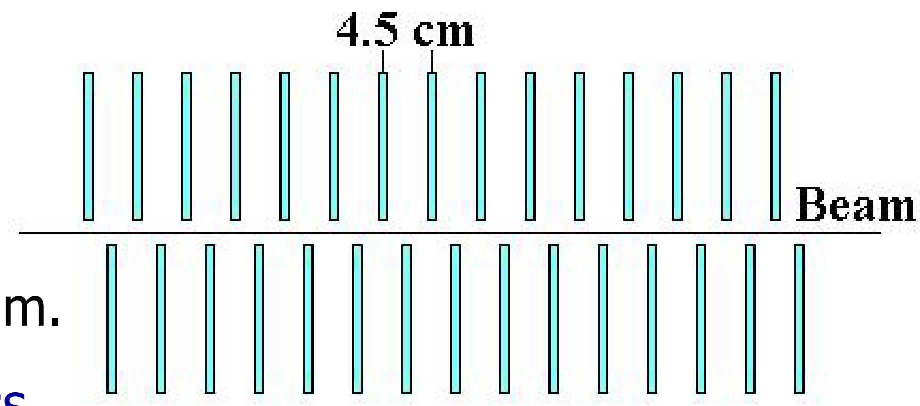
The BTeV Detector

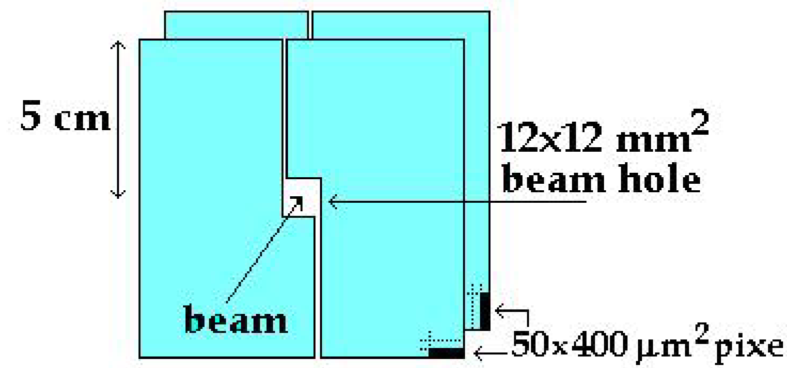
- "A supercomputer with an accelerator running through it" (technically aggressive trigger)
- Vertex trigger at trigger level 1
- RICH for particle ID
- $PbWO_4$ crystal EM calorimeter



Pixel Vertex Detector

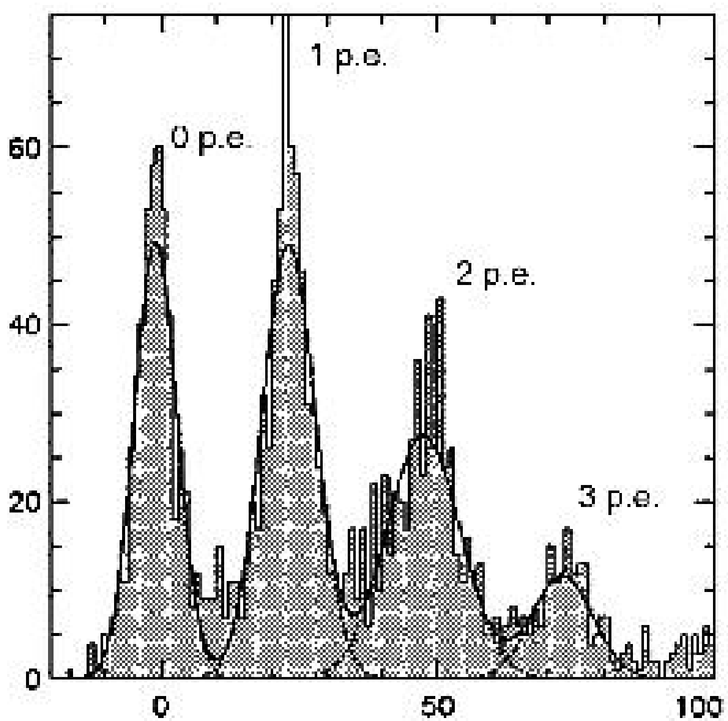
- 2.2×10^7 pixels, 10 cm x 10 cm
- 50 x 400 μm pixel size
- Achieved design resolution (5-10 μm) in 1999 FNAL testbeam.
- Demonstrated radiation hardness in exposures at IUCF.
- Final readout chip has been bench tested and will undergo final testing in FNAL test-beam in 2003.

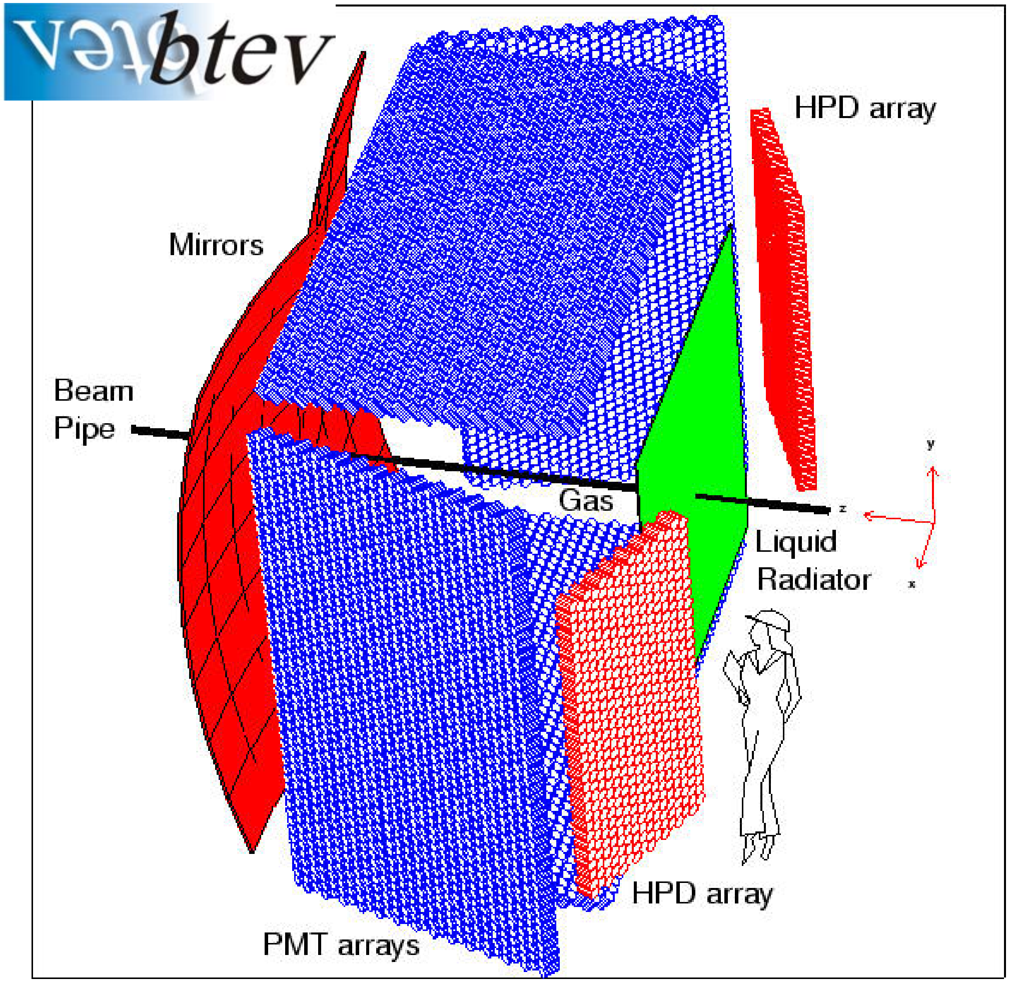




Ring Imaging Cerenkov

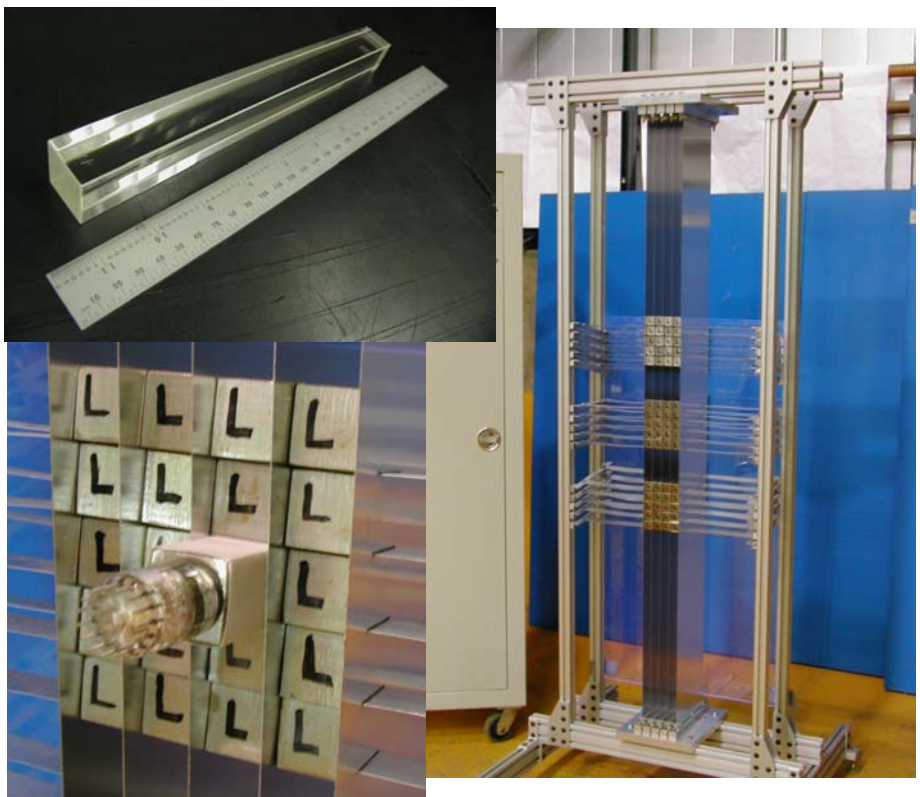
- Gas radiator (C_4F_{10}) detected on planes of Hybrid Photodiodes (944)
- Liquid radiator (C_5F_{12}) detected on array of 5000 side mounted 3" PMTs
- Developing a 163 pixel HPD
  - Bench test at Syracuse showing pulse height distribution from prototype

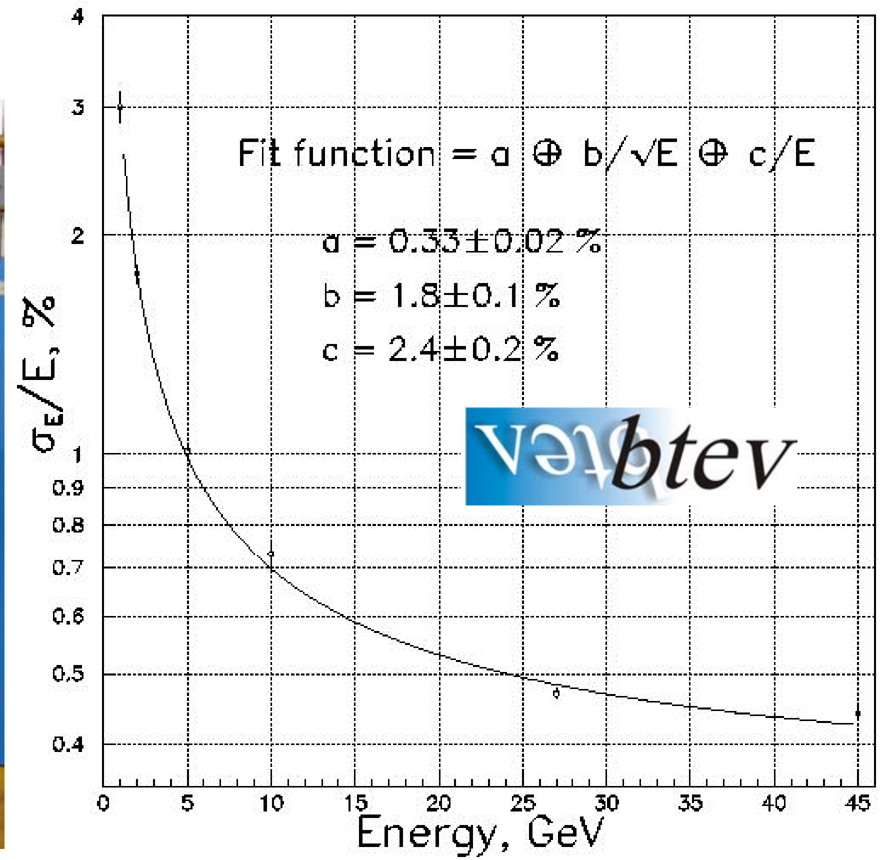




BTeV Lead Tungstate EMCal

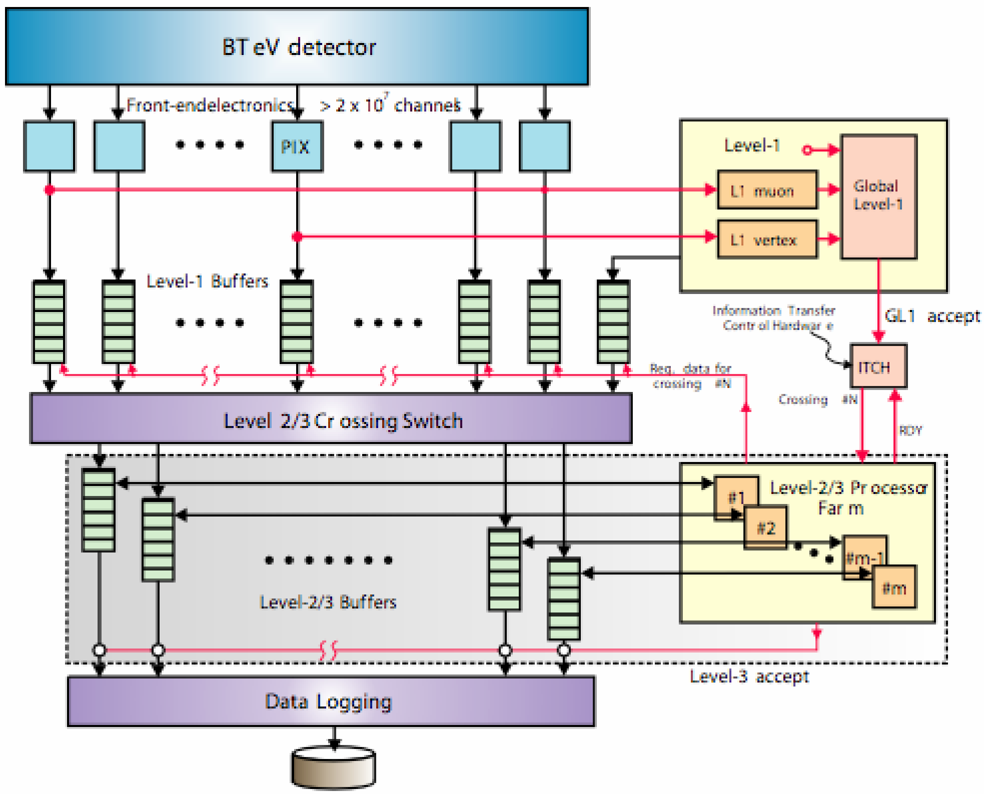
- $PbWO_4$ 28x28 mm (22 cm) crystals pioneered by CMS (but PMT readout)
- Excellent energy and spatial resolution, radiation hardness
- Resol. measured in IHEP/Protvino beam tests (stochastic term = 1.8%)
- Multiple vendors: Bogoriditsk, Russia and Shanghai, China
- 10,500 crystals in system





BTeV Trigger

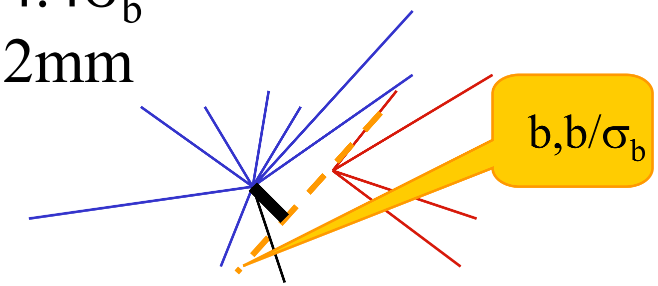
- Input rate: 800 GB/s (2.5 MHz)
- Made possible by 3D pixel space points, low occupancy
- Pipelined w/ 1 TB buffer, no fixed latency
- Level 1: FPGAs & 2500 DSPs find detached vertices, p_t
- Level 2/3: 2000 node Linux cluster does fast version of reconstruction
- Output rate: 4 KHz, 200 MB/s
- Data rate: 1—2 Petabytes/yr
- Considering *not* writing data to tape!

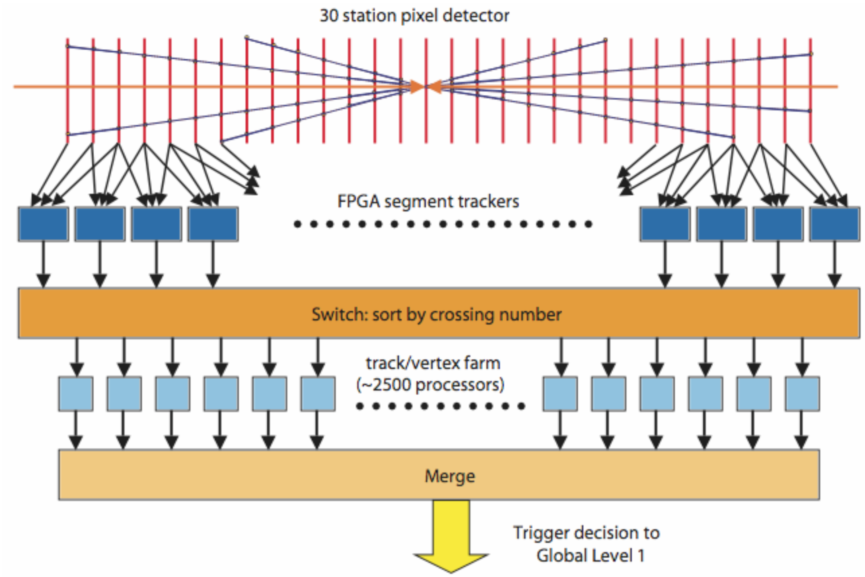


BTeV L1 Pixel Trigger

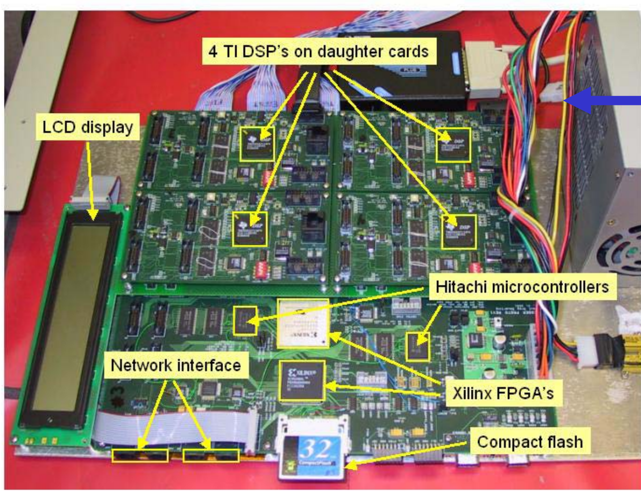
Finds primary vertex and looks for
At least 2 tracks that miss it with:

- $p_T^2 > 0.25\ (\mathrm{GeV}/c)^2$
- $b > 4.4\sigma_b$
- $b < 2\mathrm{mm}$





100/1 rejection of min-bias events



L1 Vertex Trigger prototype

- Timing tests show we are already close to the required < 350 μs L1 latency
- Speed is low by 2.7× w/old DSP
  1.8× w/new DSP

No need for hand optimized assembly code!

Fault Tolerance/Adaption

- With a system this large, the BTeV Trigger/DAQ is likely to suffer from failures at a rate that could impact effectiveness
- Human operators unlikely to be able to service simple problems or even more complex ones
- Working with Computer Scientists and Engineers to apply fault tolerance and **adaption** techniques that are being developed for real-time embedded systems such as the BTeV trigger **($5M NSF ITR** grant.)
- BTeV system represents a new level of complexity and scale
- Detect, diagnose, and recover from errors not only at the system hardware & administration level, **but also at the application level** (changing detector and algorithm thresholds!)
- Successful demonstration of small scale prototype at SuperComputing 2003 conference last month.

Illinois **Pittsburgh** **Syracuse** **Vanderbilt** **Fermilab** **NSF**

BTeV Physics Reach CKM in 10^7 s (Model Independent)

Decay	$\mathcal{B}$(B) (x10^{-6})	# Events	S/B	Parameter	Error or (Value)
$B_s \rightarrow D_s K^-$	300	7500	7	γ - 2χ	8^o
$B_s \rightarrow D_s \pi^-$	3000	59,000	3	x_s	(75)
$B^0 \rightarrow J/\psi K_S$ $J/\psi \rightarrow \ell^+ \ell^-$	445	168,000	10	sin(2β)	0.017
$B^0 \rightarrow J/\psi K^0$, $K^0 \rightarrow \pi \ell \nu$	7	250	2.3	cos(2β)	~0.5
$B^- \rightarrow D^0 (K^+\pi^-) K^-$	0.17	170	1	γ	13^o
$B^- \rightarrow D^0 (K^+K^-) K^-$	1.1	1,000	>10		
$B_s \rightarrow J/\psi \eta$	330	2,800	15	sin(2χ)	0.024
$B_s \rightarrow J/\psi \eta'$	670	9,800	30		
$B^0 \rightarrow \rho^+\pi^-$	28	5,400	4.1	α	~ 4^o
$B^0 \rightarrow \rho^0\pi^0$	5	780	0.3		

Compare to Belle/BaBar

- No B_s, B_c and Λ_b at B-factories (no comprehensive study)
- Number of flavor tagged $B^0 \rightarrow \pi^+\pi^-$ (BR=0.45×10^{-5})

	$L(cm^{-2}s^{-1})$	σ	$\#B^0/10^7s$	ε_{rec}	εD^2	#tagged
e^+e^-	10^{34}	1.1nb	1.1×10^8	0.45	0.26	56
BTeV	2×10^{32}	100μb	1.5×10^{11}	0.021	0.1	1426

- Number of $B^- \rightarrow D^0K^-$ (F$\overline{\text{ull}}$ product BR=1.7×10^{-7})

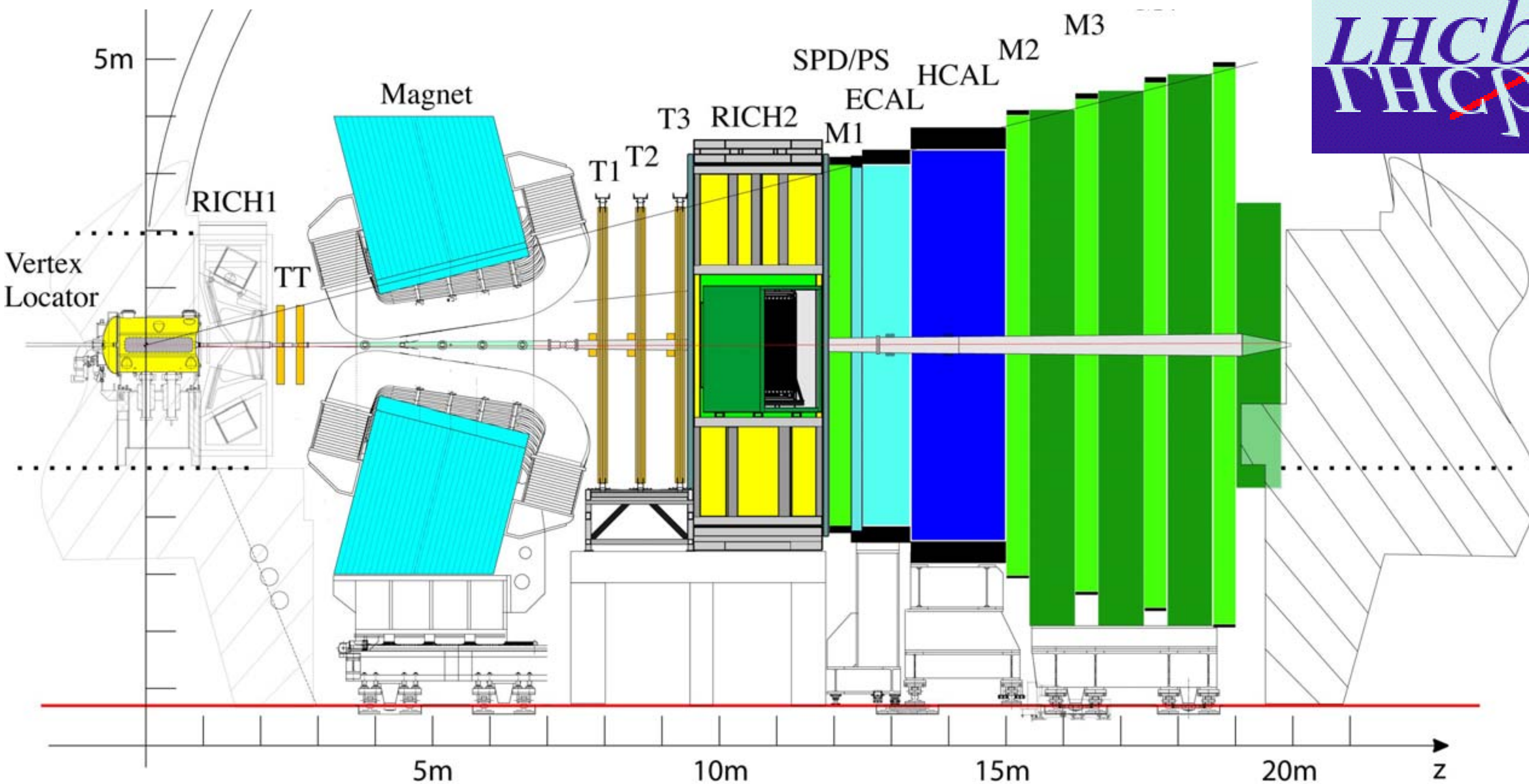
	$L(cm^{-2}s^{-1})$	σ	$\#B^0/10^7s$	ε_{rec}	#
e^+e^-	10^{34}	1.1nb	1.1×10^8	0.4	5
BTeV	2×10^{32}	100μb	1.5×10^{11}	0.007	176

Events in New Physics Modes: Comparison with B-Factories

Mode	BTeV (10^7s)			B-Factory (500 fb^{-1})		
	Yield	Tagged	S/B	Yield	Tagged	S/B
$B_s \to J/\Psi\eta^{(\prime)}$	12650	1645	>15	-	-	-
$B^- \to \phi K^-$	11000	n/a	>10	700	700	4
$B^0 \to \phi K_s$	2000	200	5.2	250	75	4
$B^0 \to K^* \mu^+\mu^-$	2530	n/a	11	~50	~50	3
$B_s \to \mu^+\mu^-$	6	0.7	>15	-	-	-
$B^0 \to \mu^+\mu^-$	1	0.1	>10	0	-	-
$D^{*+} \to D^0\pi^+, D^0 \to K\pi^+$	$\sim 10^8$	$\sim 10^8$	large	8×10^5	8×10^5	large

LHCb

- Will run at LHC (obviously)
- LHCb has higher cross-section for *b* production but BTeV believes it will get that back due to trigger, easier environment



Summary

- Flavor physics has a long history of discovery
- Flavor physics will be an equal partner to high-p_t in LHC era… and LHCb and BTeV will be capable of investigating flavor physics with the required sensitivity and flexibility needed to discover, confirm or clarify new phenomena.
- Must search beyond the streetlight!

BACKUP SLIDES

Derivation of Decay Widths

$$B^0(t) = e^{-iMt-\frac{1}{2}\Gamma t}\left[\cos\frac{\Delta Mt}{2}B^0(0) \; + \; i\frac{q}{p}\sin\frac{\Delta Mt}{2}\overline{B}^0(0)\right]$$

$$\begin{aligned}
A_{\text{tot}} &= \left\langle f_{CP}\middle|\mathrm{H}\middle|B^0(t)\right\rangle \\
&= e^{-iMt-\frac{1}{2}\Gamma t}\left[\cos\frac{\Delta Mt}{2}\left\langle f_{CP}\middle|\mathrm{H}\middle|B^0(0)\right\rangle + i\frac{q}{p}\sin\frac{\Delta Mt}{2}\left\langle f_{CP}\middle|\mathrm{H}\middle|\overline{B}^0(0)\right\rangle\right] \\
&= Ae^{-iMt-\frac{1}{2}\Gamma t}\left(\cos\frac{\Delta Mt}{2} \; + \; i\lambda\sin\frac{\Delta Mt}{2}\right)
\end{aligned}$$

$$\begin{aligned}
&\Gamma\left(B^0(t)\to f_{CP}\right) = \\
&= |A|^2 e^{-\Gamma t}\left(\cos\frac{\Delta Mt}{2} \; + \; i\lambda\sin\frac{\Delta Mt}{2}\right)\bullet\left(\cos\frac{\Delta Mt}{2} \; - \; i\lambda^*\sin\frac{\Delta Mt}{2}\right) \\
&= |A|^2 e^{-\Gamma t}\left[\left(\cos^2\frac{\Delta Mt}{2} \; + \; |\lambda|^2\sin^2\frac{\Delta Mt}{2}\right)+\frac{1}{2}\sin\Delta Mt\left(i\lambda-i\lambda^*\right)\right] \\
&= |A|^2 e^{-\Gamma t}\left[\left(\cos^2\frac{\Delta Mt}{2} \; + \; |\lambda|^2\sin^2\frac{\Delta Mt}{2}\right)+\Im(\lambda)\sin\Delta Mt\right]
\end{aligned}$$

Indirect CPV in Mixing

- Indirect CPV in Mixing occurs if |q/p| ≠ 1:

$$r_{\text{mix}}(t) = \left|\left\langle \bar{B}^0(0)\middle| B^0(t)\right\rangle\right|^2 = \left|\frac{q}{p}\right|^2 e^{-\Gamma t}\sin^2\frac{\Delta M t}{2}$$

$$\bar{r}_{\text{mix}}(t) = \left|\left\langle B^0(0)\middle| \bar{B}^0(t)\right\rangle\right|^2 = \left|\frac{p}{q}\right|^2 e^{-\Gamma t}\sin^2\frac{\Delta M t}{2}$$

- Look in semileptonic decays (wrong sign can only occur through mixing)…

$$a_{CP} = \frac{r_{\text{mix}} - \bar{r}_{\text{mix}}}{r_{\text{mix}} + \bar{r}_{\text{mix}}} = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2} = \frac{1 - |p/q|^4}{1 + |p/q|^4} = O(10^{-3})$$

- Identical to what happens in kaon system, small b/c ΔΓ is small for B_d (but maybe not for B_s)

Upper limits on Δm_s

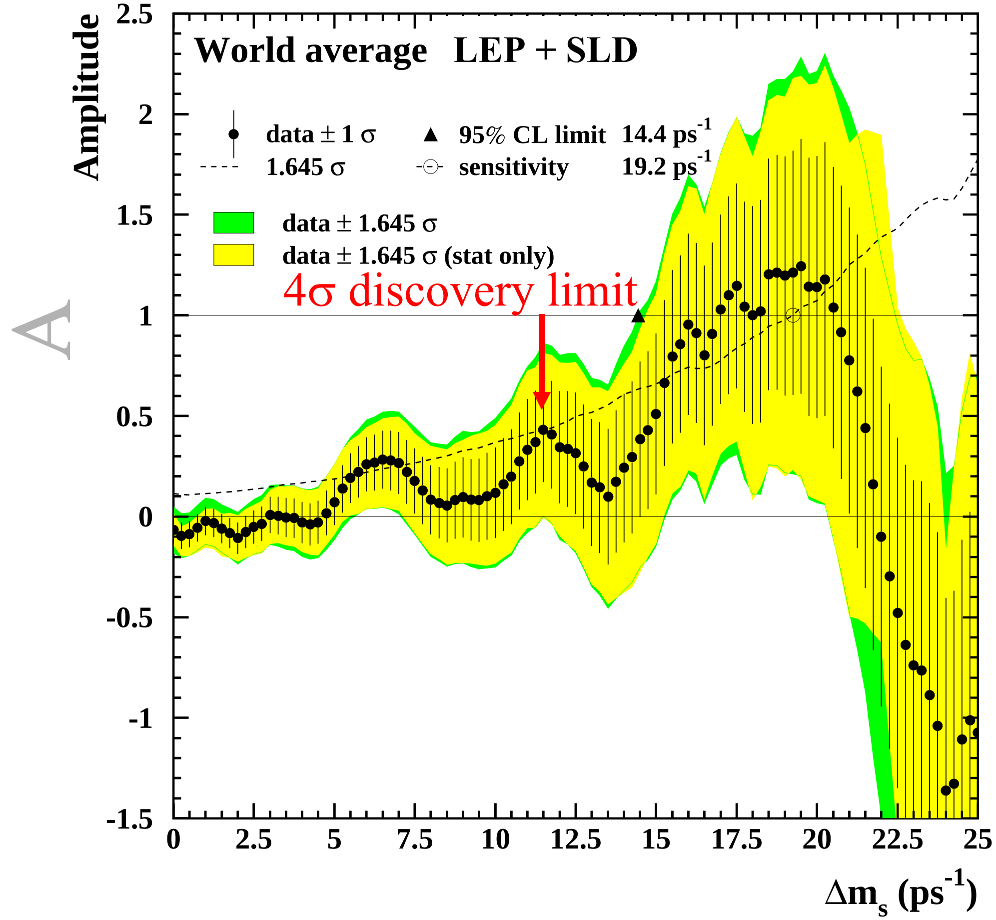
- $P(B_s \rightarrow \overline{B_s}) = 0.5 \times$

  $\Gamma_s e^{-\Gamma_s t}[1+\cos(\Delta m_s t)]$

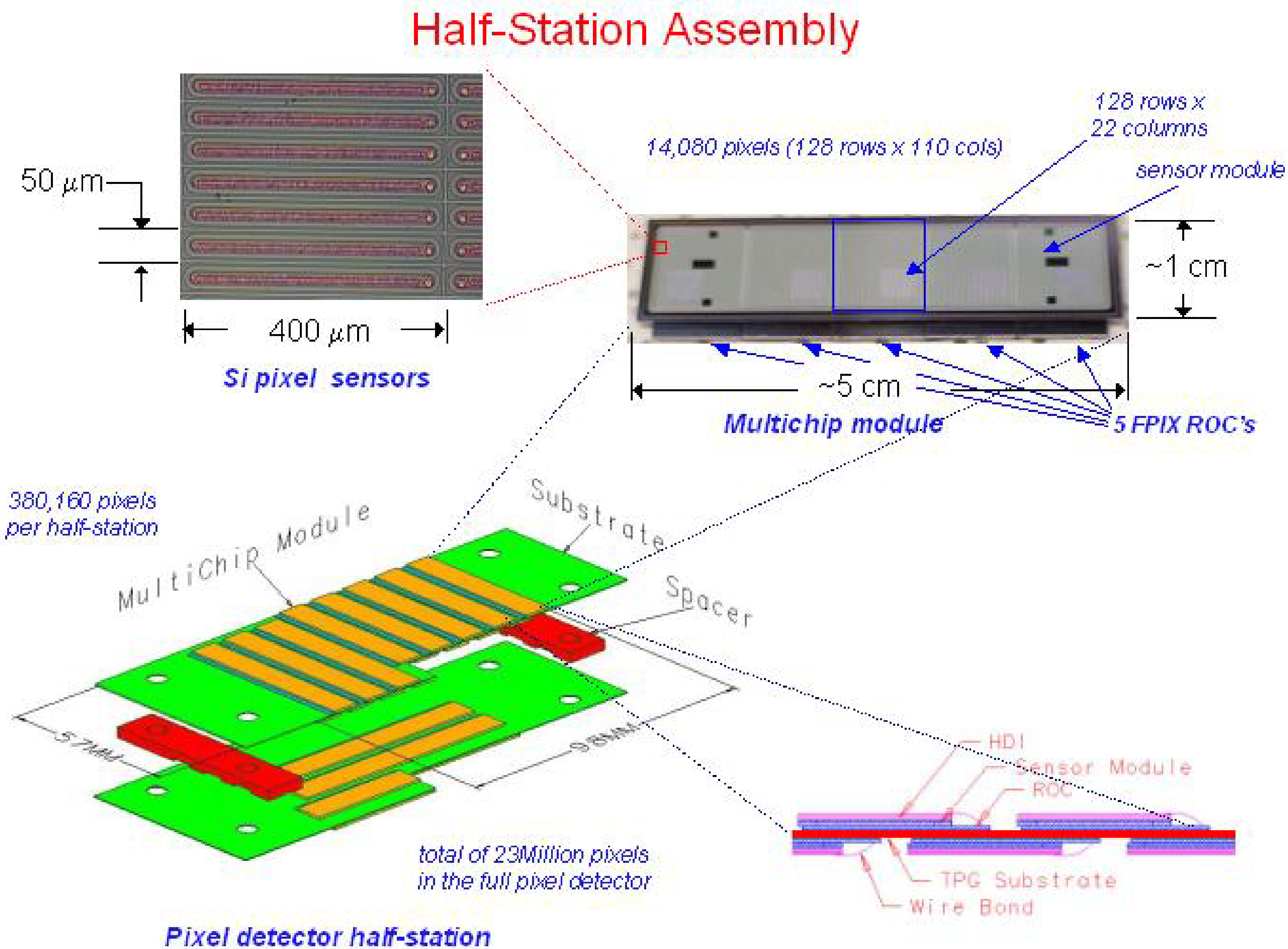
- To add exp. it is useful to analyze the data as a function of a test frequency ω

- $g(t) = 0.5\, \Gamma_s$

  $e^{-\Gamma_s t}[1+\mathcal{A}\cos(\omega t)]$



Pixel Vertex Half-Station



Ring Imaging Cerenkov

HPD Enclosure will be here

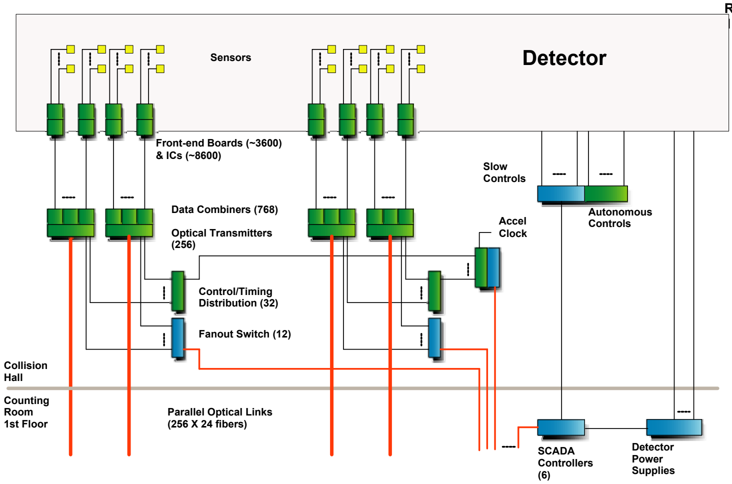
Enclosure for RICH beam test

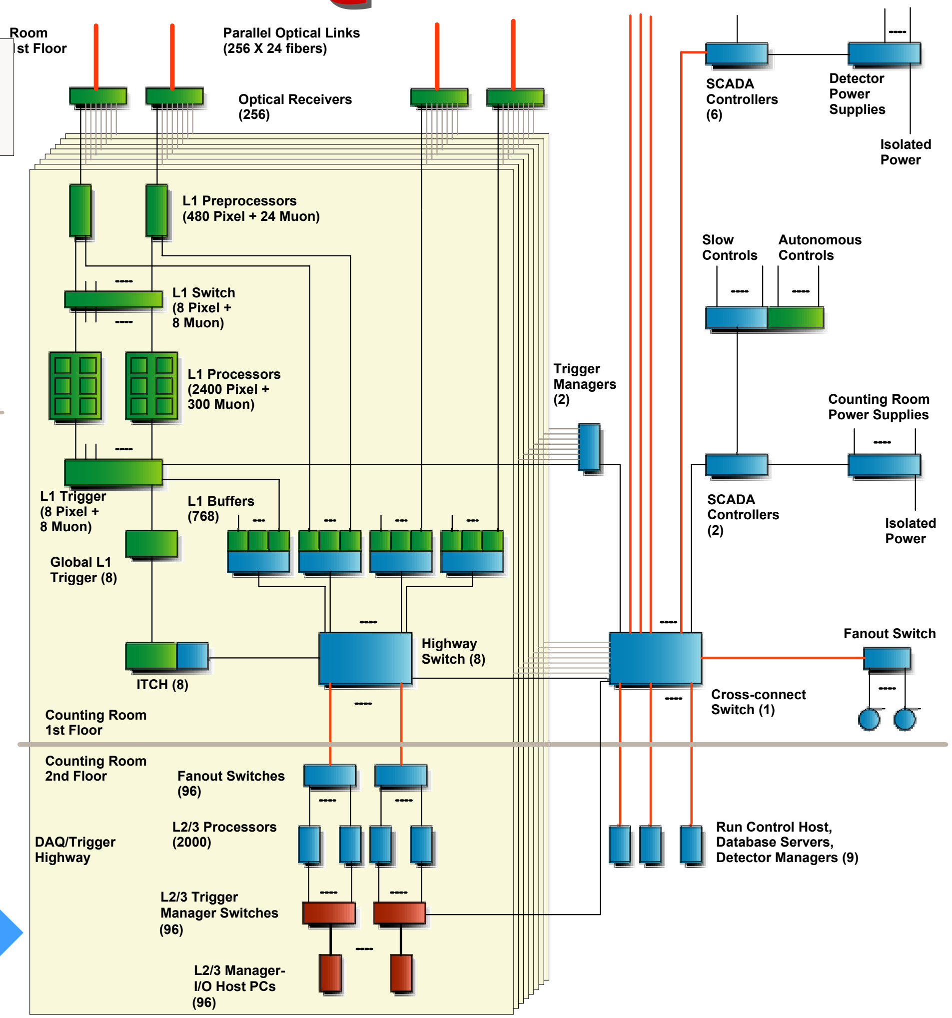
Beam

Mirror at back end

- Also testing MAPMTs

BTeV DAQ





- Changed custom switch to a commercial one to lower risk.
- DAQ is divided into 8 “Highways”
- Output data is DST and saved on disk (with duplication)